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LA JOLLA, CALIFORNIA

April, 1946

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Contribution No. 243

Reprinted from JOURNAL OF THE WASHINGTON ACADEMY OF SCIENCES
Vol. 35, No. 2, February 15, 1945

ZOOLOGY.—Malacobdella minuta, *a new commensal nemertean.*[1]

WESLEY R. COE. Osborn Zoological Laboratory, Yale University, and Scripps Institution of Oceanography, University of California. (Communicated by WALDO L. SCHMITT.)

The new species of nemertean described herein is of interest because it presents several morphological deviations from the three previously described representatives of the order Bdellonemertea. This order contains but a single genus, *Malacobdella*, the species of which are highly specialized for a commensal life within the mantle or pulmonary cavities of various mollusks. One of these species, *Malacobdella grossa* (O. F. Müller), which is specifically identical with *M. mercenaria* and *M. obesa* Verrill, is widely distributed in pelecypods on the coasts of Europe and on both the Atlantic and Pacific coasts of North America. Another species (*M. japonica* Takakura) has been reported only from the coasts of Japan. The third species was found in the pulmonary cavity of a fresh-water snail in Chile.

[1] Received September 1, 1944. Contributions from the Scripps Institution of Oceanography, New Series No. 243.

DESCRIPTION

Malacobdella minuta, n. sp., is a dwarf form, with a combination of characteristics by which it is easily distinguished from *M. grossa*, also found on the coast of California, as well as from *M. japonica*. It differs particularly from *M. grossa* in its small size when mature, in having few and relatively large gonads, arranged in a single irregular row, in having dorsolateral nephridiopores, and in the short proboscis chamber. The chief distinctions from *M. japonica* are size, arrangement and number of gonads, length of proboscis sheath, and position of posterior nerve commissure. Minor differences from each of these species are indicated in the following paragraphs:

Length of sexually mature type specimen only 5 to 8 mm, according to state of contrac-

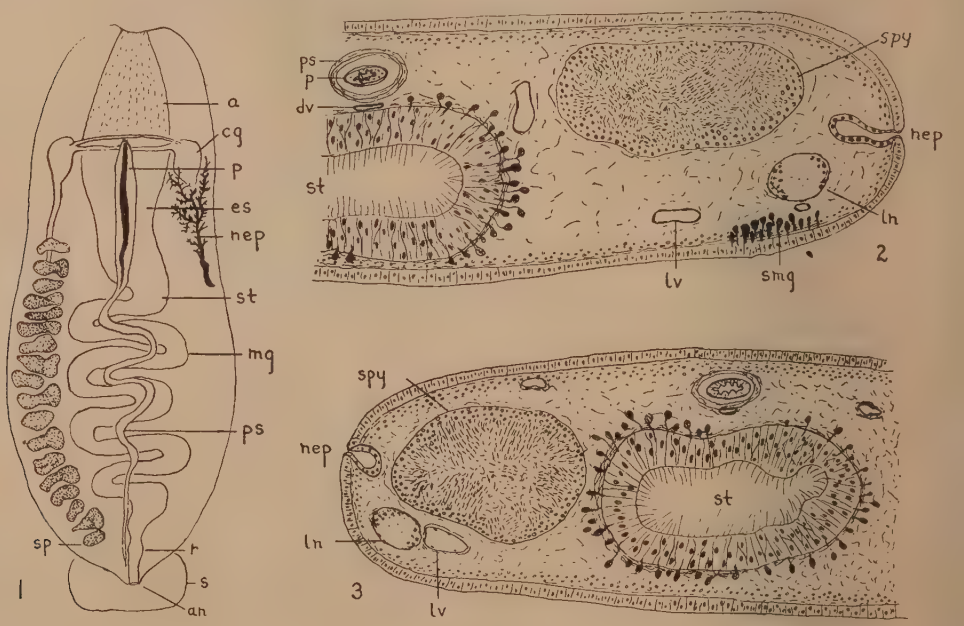
tion, as compared with 20 to 50 mm in the other two marine species. Width 2 mm.

Color whitish and translucent; intestine pale yellow; spermaries opaque white.

Proboscis.—The proboscis sheath extends nearly the entire length of the body, as in *M. grossa*, while this organ is only two-thirds as long as the body in *M. japonica* (Takakura, 1897; Yamaoka, 1940). The proboscis fills most of the cavity of the rhynchocoel and is therefore coiled only as much as the sheath. It has only a single chamber and this extends posteriorly somewhat less than half the length of the body (Fig. 1). After eversion it is withdrawn by a long retractor muscle which extends the entire length of the sheath. Near the base of the sucker this long, slender muscle passes through the end of the sheath and some of its fibers become interlaced with fibers from the dorsal body wall, as Riepen (1933) and others have described for *M. grossa*. The proboscis chamber is relatively much shorter and the retractor muscle correspondingly longer than in *M. grossa*.

Vascular system.—The two lateral blood vessels are much branched, as in other species of the genus, and have the usual dorsal cephalic anastomosis. In the brain region there is a second anastomosis on the dorsal side of the esophagus. From this anastomosis the dorsal vessel originates and the three longitudinal vessels are united posteriorly on the dorsal side of the rectum.

Excretory system.—The single pair of nephridia extend from near the brain through most of the anterior half of the body (Fig. 1). The profusely branching tubules lie in the parenchyma dorsal to the lateral nerves and adjacent to the main lateral blood vessels. They unite posteriorly to form a pair of large efferent ducts which lead to the exterior on the dorsolateral surfaces of the body (Figs. 2, 3). In this respect the species resembles *M. japonica* and differs from *M. grossa*. In the latter the nephridiopores are ventrolateral.



Malacobdella minuta, n. sp.: Fig. 1.—Diagram of organ systems from dorsal surface, showing atrium (*a*), anus (*an*), cerebral ganglia (*cg*), esophagus (*es*), midgut (*mg*), one of the nephridia (*nep*), proboscis (*p*), proboscis sheath (*ps*), rectum (*r*), sucker (*s*), spermaries (*sp*) and stomach (*st*). Fig. 2.—Portion of transverse section through posterior portion of anterior half of body, showing right efferent nephridial duct (*nep*) opening on dorsolateral surface. Other letters indicate: *dv*, dorsal blood vessel; *ln*, lateral nerve cord; *lv*, lateral vessel; *p*, proboscis; *ps*, proboscis sheath; *smg*, submuscular glands; *spy*, spermary; *st*, stomach with columnar ciliated epithelium surrounded by gland cells. Fig. 3.—Portion of transverse section of body, showing left efferent nephridial duct (*nep*) on dorsolateral surface. Other letters as in Fig. 2.

The efferent ducts lie at the posterior end of the nephridial system and in the region where the stomach enters the midgut. This is also the region where the lateral blood vessels move from the dorsolateral to the ventrolateral portion of the parenchyma and a short distance behind the most anterior gonads (Fig. 1).

Digestive system.—The broad atrium extends from near the tip of the head to the brain commissures where the proboscis opens through its dorsal wall. Posterior to the proboscis opening the digestive canal continues as the esophagus without change in the size of the lumen or in the character of the lining epithelium of short ciliated cells. In the region of the nephridiopores and the most anterior gonads the lumen becomes narrower, the ciliated epithelium more highly columnar and the large, subepithelial gland cells in the parenchyma on the external border of the epithelium become more numerous. This part of the gut is correctly designated as the stomach (Figs. 1, 2, 3). This specimen shows no indication of the caecum which Riepen (1933) describes as occurring between foregut and midgut in *M. grossa*. There is no abrupt change but only a gradual transition in the lumen as well as in the epithelium between esophagus and stomach and between stomach and midgut.

Posterior to the stomach the slender midgut bends alternately to left and right, forming three loops or convolutions on the right side of the body and four on the left. The midgut terminates in the median rectum which opens on the dorsal side of the sucker (Fig. 1).

Nervous system.—The two cerebral ganglia are widely separated by the broad atrium (Fig. 1) and are connected by the usual small dorsal and large ventral commissures. Each ganglion has but a single fibrous core and is without division into dorsal and ventral lobes. At the posterior end of the body the lateral nerve cords are united by a slender commissure situated on the dorsal side of the rectum and in close connection with the anastomosis of the three longitudinal blood vessels. In this respect the species resembles *M. grossa* and differs from *M. japonica*. In the latter the commissure is stated to lie in the sucker and posterior to the anus (Takakura, 1897; Yamaoka, 1940).

Reproductive system.—In the single male available for study the gonads are situated in a single irregular row on each side of the body. In this specimen, which was sexually mature, there are 18 pairs of large spermaries filled with apparently mature spermatozoa (Fig. 1). In this respect *M. minuta* differs from either of the two other marine species, in which the gonads are relatively small and very numerous. In this new species they are arranged much as in typical hoplonemerteans. Female at present unknown.

Habitat.—Commensal in the mantle cavity of *Yoldia cooperi* Gabb. Collected by Dr. Martin Johnson off Point Loma, southern California, at a depth of 40 meters.

Type in Peabody Museum, Yale University.

The four species of *Malacobdella* at present known may be distinguished by the following key:

1. Commensal in marine pelecypods.....2
   Commensal in fresh-water gastropod. *auriculae*
2. Proboscis sheath nearly as long as body; posterior commissure of nerve cords on dorsal side of rectum.....3
   Proboscis sheath only two-thirds as long as body; posterior commissure of nerve cords in sucker..... *japonica*
3. Nephridiopores on dorsolateral surfaces; gonads large, situated in a single irregular row on each side of body..... *minuta*
   Nephridiopores on ventrolateral surfaces; gonads relatively small and very numerous, irregularly scattered..... *grossa*

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Contribution No. 244

Reprinted from SCIENCE, February 2, 1945, Vol. 101, No. 2614, page 114.

PIGMENT AND BIOCHROME

MY colleague, Professor Fox, has dragged into the open a feud which has been smoldering between us for many years.[1] While the mores of our species, both as to the use of words, and the use of pigments themselves, are little influenced by arguments, it has seemed to me worth while to put some of my contentions in this field on record again.

I have long been irked by some of the prevailing uses, in biology, of the word "pigment." Dr. Fox admits the force of these objections, in part, though he insists upon retaining this word as a convenient vernacular (?) term. For more accurate scientific usage, he has adopted the suggestion of a professor of Greek, and substituted a new word "biochrome."

Whether it is reasonable to set up, as a special class, all the colored substances which can be extracted from animals or plants, in contrast with those substances which do not happen to be colored, is decidedly debatable. However, if we grant the desirability of such a term, "biochrome" would seem to meet the requirements pretty well. That "pigment" does not do so, I have already argued.[2] For this word has a definitely functional connotation, which we can hardly escape. In the inorganic world, colored substances are "pigments" only in so far as they are used as such. Thus lead chromate is (or may be) a pigment; copper sulfate never is. Save for an unfortunate precedent, I can see no excuse for applying any different criterion in the organic world. Why every colored substance, derivable in any way from a living organism, should forthwith become a "pigment" is difficult to understand.

1 SCIENCE, November 24, 1944.
2 *Scientific Monthly*, April, 1937.

Needless to say, I am offering no general protest against the use of the word "pigment" in biology. I have used the word freely, in connection with my own studies and shall continue to do so. But I believe that the word, when transferred to the organic world, should retain its functional significance. There is no propriety in calling a substance a "pigment" except in so far as it is used by the organism to influence its color scheme. I trust that it is no longer necessary to insist that the *appearance* of an animal is at times one of its important biological assets. Thus, melanin, the carotenoids, guanine and some other substances, occasionally even hemoglobin, may play the functional role of pigments. In so saying, let us repeat, we are not thereby assigning these substances to a definite physical and chemical category.

My chief protest against current usage in this field relates to the expression "respiratory pigment." We are here combining words belonging to two utterly different vocabularies. It is like talking about a "locomotor enzyme" or an "invertebrate catalyzer"! Dr. Fox, in his recent communication to SCIENCE, has given some theoretical reasons for believing that the same features of molecular organization which give to certain substances their color may likewise render them available as oxygen carriers. But even if this association between these attributes should prove to be true, we should hardly be justified in such a bit of semantic miscegenation as we have in "respiratory pigment"! Nor would "respiratory biochrome" be much better.

F. B. SUMNER

SCRIPPS INSTITUTION
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LA JOLLA, CALIF.

Contribution No. 246

THE CAUSE MUST HAVE HAD EYES

By DR. FRANCIS B. SUMNER
Professor of Biology, Scripps Institution of Oceanography, La Jolla, California.

Reprinted from THE SCIENTIFIC MONTHLY, March, 1945, Vol. LX, pp. 181–186.

THE CAUSE MUST HAVE HAD EYES*

By FRANCIS B. SUMNER

"Die Ursache muss Augen gehabt haben." Thus wrote the zoological philosopher August Pauly, forty years ago, in contemplating the magnificent tail feathers of the peacock, spread out to view and waved with every appearance of self-conscious pride.[1] Pauly was a Lamarckian of an extreme type. He rejected the Darwinian theory of natural selection as materialistic and substituted the idea that the organism was very largely self-created, responding to its own feelings, desires, and fears with appropriate processes of growth and differentiation in every part of the body. That changes thus originating were transmitted to succeeding generations he did not think it necessary to prove.

In view of more recent developments in our knowledge of heredity, the speculations of Pauly and some of his contemporaries now seem fantastic in the extreme. They are, however, interesting reading. We may even recognize a certain measure of truth in them. The Lamarckian requirements respecting heredity have not, of course, been met. On the other hand, the morphogenic effects of sensorimotor processes—including some processes which, in ourselves, we designate as psychical—have been established by evidence that was but little known to the Lamarckians. That some fishes, for example, can regulate the formation of pigment cells in their skins in response to what they see with their eyes is a fact now familiar to biologists.[2] But there is no evidence to show that effects produced in this way may be accumulated through inheritance, if successive generations of fishes are subjected to the same visual environment. Until such wholly unexpected evidence is forthcoming, it would be foolish to suggest that any of the fixed colors and color patterns of animals, i.e., those not subject to change with change of present environment, are the product of past self-adjustment to ancestral environments.

Nevertheless, the phenomena that have been discussed since Darwin's day under such names as 'protective resemblance,' 'concealing coloration,' and 'mimicry' have maintained their major position in biological inquiry. As required reading for a graduate student in zoology—I might add, for a graduate student in general physiology or biochemistry or genetics—I should recommend the volume by Hugh B. Cott, *Adaptive Coloration in Animals*.[3] The reader who follows Cott's evidence attentively and without prejudice may not perhaps accept every one of the author's interpretations, but he is not likely to be patient with anyone who might suggest that we are dealing here with an endless succession of coincidences. Throughout large sections of the animal kingdom he will encounter color patterns, structures, and even modes of behavior that rather plainly have been evolved with primary reference to the animal's *appearance*. He might well be moved to declare, and with more reason than Pauly, that "the cause must have had eyes." Yes, indeed, but *whose* eyes? Pauly was thinking of the animal's own eyes and believed that impressions received through them exercise morphogenic effects upon their possessor.

The natural selectionist, on the contrary, has in mind the eyes of the animal's enemy or prey. That this process of selection is part of the grand strategy of nature few biologists now question. The theory has passed through various phases of triumph and defeat ever since the time of Darwin. It has been both proved and disproved to the satisfaction of many biologists. But it has emerged at long last, in somewhat altered form to be sure, but possessed of nearly all the directive powers that Darwin claimed for it. Whether natural selection can rightfully be called a *creative* principle is wholly a matter of definition.

That such patterns of color and structure as make for concealment or hinder recognition actually operate in a high degree to save the lives of the animals concerned might seem to the layman to require no further proof. But this assumption has been challenged or even fiercely denied on theoretical grounds by those useful, if sometimes irritating, "de-

* Contributions from the Scripps Institution of Oceanography, New Series. No. 246.

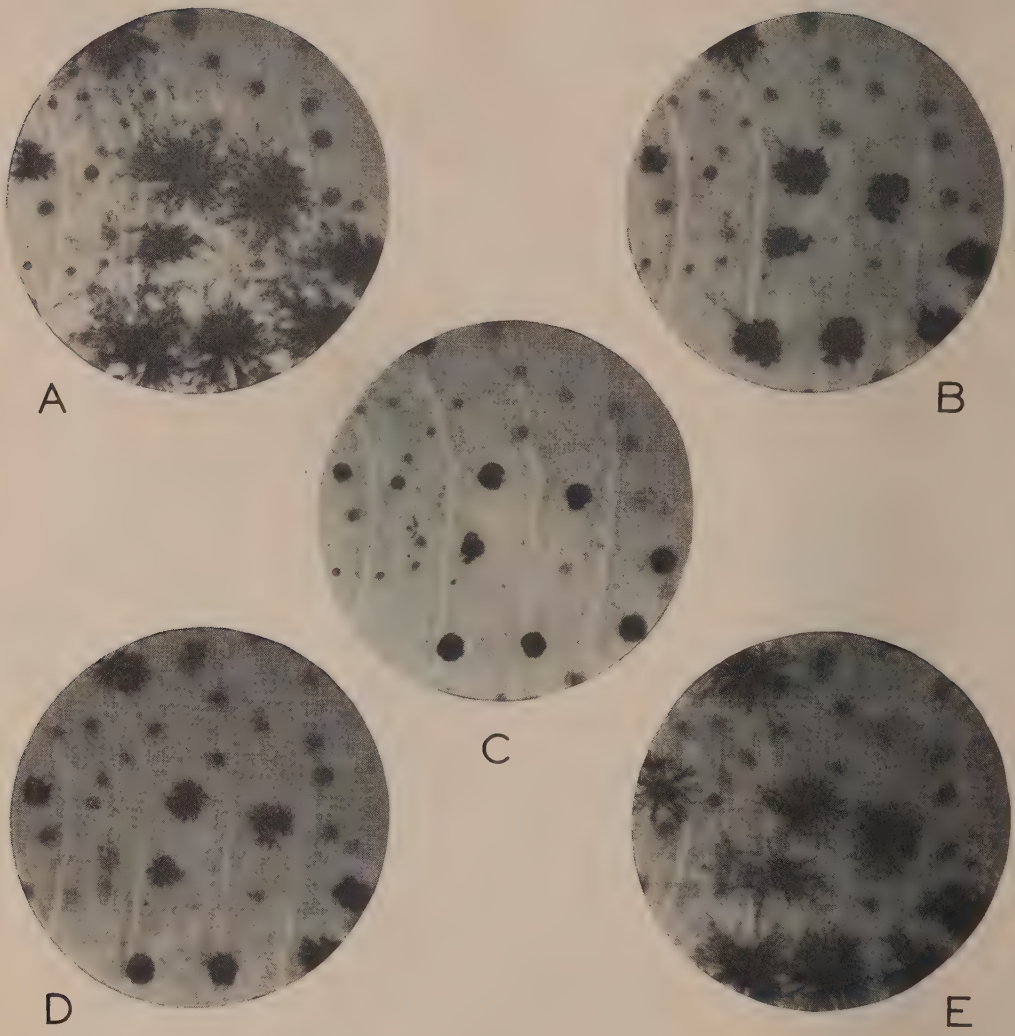

FIG. 1. GROUP OF LIVING CHROMATOPHORES ON SCALE OF FISH

SHOWING DISPERSED AND CONCENTRATED STATE OF MELANIN GRANULES UNDER CHEMICAL INFLUENCE. THESE PARALLEL THE CHANGES THAT ARE UNDERGONE AS A RESULT OF NERVOUS STIMULI. *A*, STATE OF NEARLY MAXIMUM DISPERSION OF MELANIN. *B*, PARTIAL CONCENTRATION, $4\frac{3}{4}$ MINUTES AFTER TREATMENT WITH ADRENALIN. *C*, MAXIMUM CONCENTRATION, 15 MINUTES AFTER TREATMENT WITH ADRENALIN. *D*, PARTIAL DISPERSION, $4\frac{1}{2}$ MINUTES AFTER SUBSTITUTION OF URETHANE. *E*, MAXIMUM DISPERSION, $7\frac{1}{6}$ MINUTES AFTER SUBSTITUTION OF URETHANE. THE SPECIES OF FISH USED IN THE EXPERIMENT WAS *Fundulus parvipennis*.

bunkers'' in science. The naturalist himself, be it said, is not usually satisfied with ''unavoidable'' conclusions when these are not supported by evidence. And so various experimental tests have been conducted on the question whether, in reality, ''protective coloration'' does protect.[4] While such data are admittedly not yet adequate in amount, they are, on the whole, confirmatory of the common-sense judgment of the unsophisticated person.

The case is, of course, most convincing when we consider those animals that are capable of conforming their color scheme, from moment to moment, to that of the surface on which they happen to rest. It is doubly

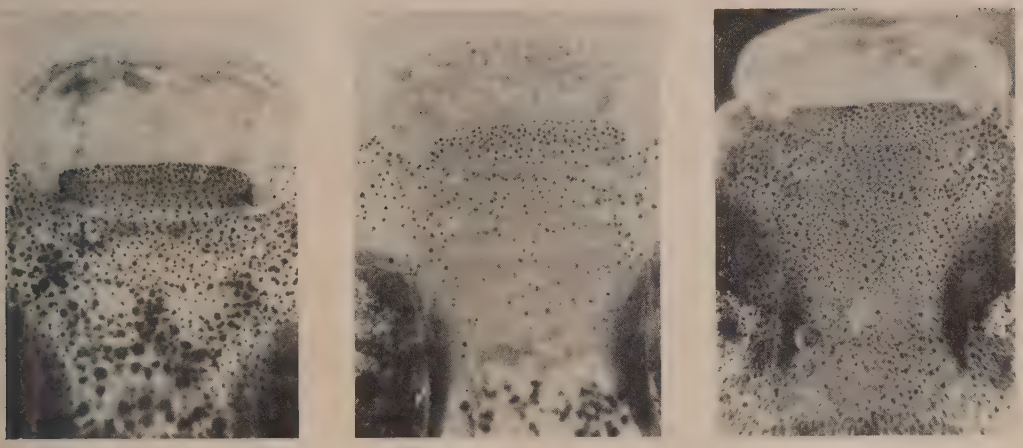

FIG. 2. VIEWS OF THE SAME INDIVIDUAL (*LEBISTES RETICULATUS*)
THE PHOTOGRAPHS OF THIS FISH WERE TAKEN WHILE IT WAS UNDER INFLUENCE OF ADRENALIN AND SHOW THE EFFECTS OF BACKGROUND UPON NUMBER OF CHROMATOPHORES. *A*, AFTER HAVING BEEN BORN AND REARED FOR 14 MONTHS ON BLACK. *B*, AFTER TRANSFER TO WHITE FOR 16 DAYS. *C*, AFTER RETURN TO BLACK FOR 16 DAYS.

convincing in those cases where not only general color tone but also the distribution of color (i.e., the pattern) is involved, as is true of many bottom-dwelling fishes.[5] Here we have a mechanism involving some of the chief organ systems of the body and operating in such fashion that no function can plausibly be ascribed to it except the concealment of the animal in question.

In the attainment of this result two sets of eyes are concerned: those of the predators, in search of their prey, and those of the potential prey, taking refuge in these self-effacing color reactions.

Various far-fetched explanations have been offered for the existence of such a mechanism, other than the obvious and almost certainly true one of affording protection to the organism. These perversions of scientific thinking spring from the insistence by a certain type of mind upon finding an immediate physical or chemical explanation for every organic phenomenon. Adaptations for concealment, or indeed *adaptations* of any type, are rejected as "teleological" and *ipso facto* unscientific.[6]

My own experiments in this field[7] consisted in exposing to the attacks of predators mixed lots of living fishes that contrasted in widely different degrees with the background employed. Such experiments were made possible by a circumstance that has not thus far been mentioned here. Fishes, and some other organisms, in addition to undergoing rapid and quickly reversible changes of appearance in response to changes in the background, may undergo changes which are much more enduring. The former are due to the shifting of the pigment particles within the color cells of the skin, with the result that these particles are either spread out into full view or withdrawn (partly) from sight (Fig. 1). The more enduring changes, resulting from longer subjection to the visual stimuli, are due to the actual production of new pigment or pigment cells, or to the loss of pigment previously present (Fig. 2). This fact makes it possible to effect modifications in the shade of fishes which will be lasting enough for the requirements of an experiment such as the present one (Fig. 3).[8] It seems to be impossible, however, to fix permanently a given pigmental condition, whether light or dark, even by keeping the fishes (at least *Lebistes*) night and day, from birth, on a given background. The responses of such fishes to a new background are delayed but thoroughgoing.[9]

More than 3,500 small fishes (*Gambusia*), thus treated, were subjected to attack by three different species of predators, a diving bird, a wading bird, and a larger species of fish. In an extensive series of experiments the numbers of fishes caught upon the back-

ground with which they contrasted more strongly averaged nearly twice the numbers caught upon the less contrasting background.[10] Results such as these were obtained, in some cases, as much as 20 hours after the period of "conditioning" had ended, and when the contrast with the experimental background in question had greatly diminished.

It has been claimed by certain critics of the protective coloration "hypothesis" that quiescence on the part of the sought-for animal, rather than concealment through camouflage, is the chief factor in averting its capture. This may be true for some predators and some prey, but it was shown by special experiments to be unfounded in the case of those here concerned.

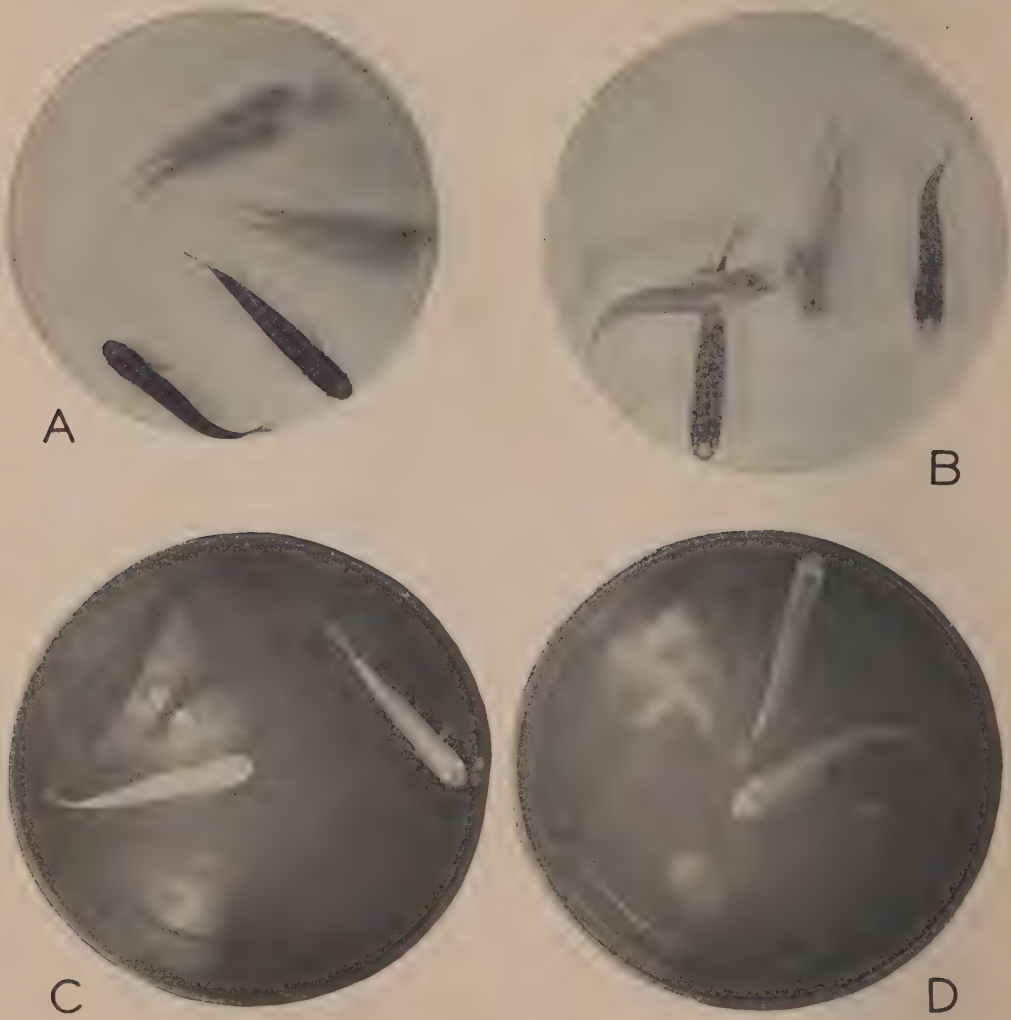

FIG. 3. INFLUENCE OF DARK AND PALE BACKGROUNDS ON *GAMBUSIA*

A, TWO OF THESE FOUR SPECIMENS HAD BEEN KEPT IN A BLACK TANK FOR ABOUT 7 WEEKS; TWO IN A WHITE TANK FOR AN EQUAL PERIOD. TAKEN ON PALE-GRAY BACKGROUND 15 SECONDS AFTER THE FISHES WERE TRANSFERRED. *B*, THE SAME FISHES AS IN *A*, AFTER REMAINING 24 HOURS ON THE PALE-GRAY BACKGROUND. *C*, FOUR FISHES WITH SAME PREVIOUS HISTORY AS IN *A*, BUT TAKEN 20 SECONDS AFTER TRANSFER TO A BLACK BACKGROUND. (THE WHITE FISHES APPEAR SOMEWHAT TOO PALE IN THIS PHOTOGRAPH.) *D*, SAME FISHES AS IN *C*, PHOTOGRAPHED AFTER REMAINING 27 HOURS IN THE BLACK BOWL. THE SPECIES IS *Gambusia affinis*.

That this capacity for adjustment to a changed visual environment has been perfected through natural selection is the more readily believable, since we know that the capacity in question differs greatly in various kinds of fishes, while those of us who have experimented in this field know that even different individuals of the same species may vary widely in this respect. The nature of the physico-chemical mechanism by which these more rapid color responses are brought about has been subjected to an almost incredible amount of analytic study in the past half century, until it has taken its place as one of the outstanding problems of comparative physiology.[11]

Relatively very few such studies, on the other hand, have been devoted to those pronounced quantitative changes in the amount of pigment present, or in the number of pigment cells, which result from more protracted subjection to a new optical environment.[12] The reasons for this emphasis are obvious. Any experiment upon these quantitative phenomena involves months of time, instead of days or hours. It likewise calls for the use of difficult biochemical technique that the great majority of zoologists are ill-equipped to employ. However, some highly interesting, as well as fundamental, biological problems lie in this field.

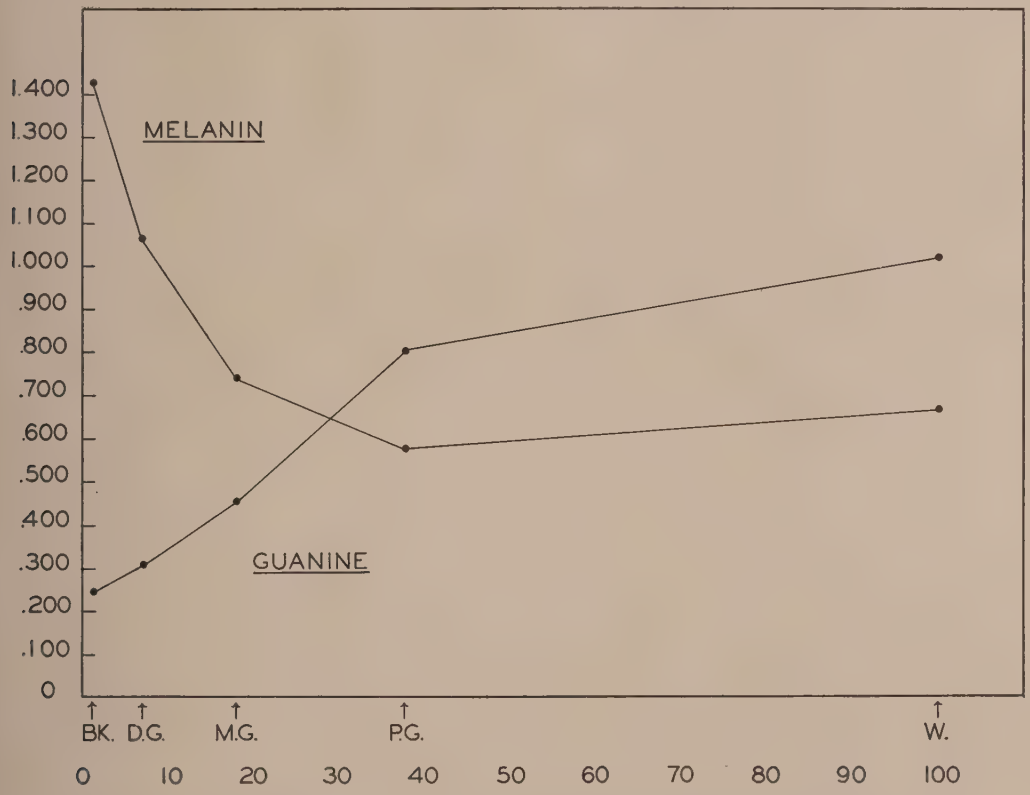

FIG. 4. RELATIONSHIP OF PIGMENT TO BACKGROUNDS OF VARYING ALBEDO

COMPARISON OF CURVES FOR MELANIN AND GUANINE IN THE SKINS OF *Girella nigricans* AFTER SUBJECTION OF THE FISHES FOR 4 MONTHS TO 5 BACKGROUNDS OF VARYING ALBEDO. ABSCISSAS = ALBEDOS, REGARDING WHITE (W) AS 100 PER CENT. ORDINATES = MG. OF THE PIGMENT PER GRAM OF WET WEIGHT OF FISHES.

After four months' subjection of one species of fish, *Girella nigricans*, to backgrounds of differing albedo (ratio of reflected to incident light), I found that the amount of black pigment (melanin) was about twice as great, per unit of weight, in fishes from the black bowls as in fishes from the white ones.[13] The amount of the white pigment (guanine), on the contrary, was more than four times

as great in the white-adapted as in the black-adapted fishes.[14] Interesting series of intermediate values were shown in connection with the intermediate albedos (Fig. 4).

This reciprocating relation between melanin and guanine in fishes was first pointed out, so far as I know, by Kuntz, nearly thirty years ago, and the matter was discussed somewhat later by a few other investigators.[15] These writers recognized that dark backgrounds favored the production of melanin and inhibited the production of guanine, while pale backgrounds had the opposite effect. They did not, however, undertake to measure these substances or to establish any quantitative relations between the stimulus and the amount of the pigment formed.

A third series of pigments, known as carotenoids, figure in the color changes of fishes, though far less of a precise nature is known about them in this relation. These substances are yellow, orange, or red in color. The cells that contain them, known as xanthophores and erythrophores, respond, as do the melanophores and guanophores, to stimuli received through the eyes. In some cases we have highly specific responses to the color of the background, as is well shown in the colored plates of Mast (*op. cit.*). Quantitative studies seem to indicate, however, that these specific responses of appearance relate only to the visibility of the pigment and that the actual quantity, at least of the yellow pigment xanthophyll, is not affected by the color (as distinct from the shade) of the background. Thus, more xanthophyll could be extracted from black-adapted fishes (*Girella,* at least) than from yellow-adapted ones, even though the former appeared black and the latter distinctly yellow.[16]

It is important to recognize that the two substances here chiefly considered, melanin and guanine, though widely different chemically, agree in being products of the destructive metabolism of protein. They are, broadly speaking, "waste products," and their elimination may be regarded as a process of excretion.[17]

The outstanding fact revealed by these experiments is that the course of protein metabolism, and the production of two important metabolites, melanin and guanine, is strongly influenced by the visual field of the fish, and influenced in such a way as to make for the animal's concealment. These fundamental organic processes are thus caused to change their course in the interest of superficial appearance, and this with no apparent effect upon the growth of the fishes.[18]

If these two pigments (three, if we follow Millot) actually function as excretory products, it is surely surprising that the necessary excretory balance should be maintained through reciprocal adjustments in the production of substances so widely unrelated chemically. Plainly, there are physiological (shall we not say psychobiological?) problems here that call for extensive future investigation.[19]

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4. Carrick, R. 1936. *Trans. Roy Ent. Soc.,* London, 85 : 131–139 ; Cesnola, A. P. di. 1904. *Biometrika,* 3 : 58–59 ; Isely, F. B. 1938. *Ecology,* 19 : 370–389 ; Poulton, E. B. and Sanders, C. B. 1898. *Brit. Assn. Adv. Sci. Rept.,* 906–909 ; Sumner, F. B. (see footnote 7) ; Young, R.T. 1916. *Jour. Exp. Zool.,* 20 : 457–507.
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6. I have dealt with this class of objectors in *Amer. Nat.,* 69 : 245–266 (1935).
7. *Proc. Nat. Acad. Sci.,* 20 : 559–564 (1934) ; 21 : 345–353 (1935) ; *Amer. Nat.,* 69 : 245–266 (1935).
8. Poulton ("Colours of Animals," p. 82) tells us that "The interior of a minnow-can is painted white in order that the bait may become light-colored and thus conspicuous in the dark water where the pike or perch is likely to be found." I was unaware of this statement when my experiments were undertaken.
9. Sumner and Wells. 1933. *Jour. Exp. Zool.,* 64 : 377–403.
10. The figures for those eaten or seriously injured, excluding the results of a few special experiments in which the reversal of background had been continued too long, were 948 and 505, respectively.
11. Professor G. H. Parker and a number of collaborators, at Harvard University, have been leaders in our country in this field (see article by Parker in the March, 1943, issue of this MONTHLY).
12. Our knowledge in this field was summarized by me a few years ago (1940) in *Biological Reviews,* 15 : 351–375.
13. *Biol. Bull.,* 84 : 195–205 (1943).
14. This use of the word "pigment" seems to me legitimate, since guanine here actually functions as a pigment, markedly affecting the color (broadly speaking) of the fishes.
15. See particularly papers by Kuntz. 1915–1916. *Bull. U. S. Bur. Fisheries,* 35 : 1–29 ; Murisier. 1920–1921. *Revue Suisse de Zoologie,* 28 : 45–97. 149–195, 243–299 ; Millot. 1923. *Bull. Biol. de la France et de la Belge,* 57 : 261–363.
16. Sumner and Fox. 1935. *Jour. Exp. Zool.,* 71 : 101–123.
17. Kuntz has pointed out that, regardless of background, melanophores are continually being discharged through the skin of a flounder.
18. My own experiments are not quite decisive on this point. If any such trophic effect of the background exists, it is slight and inconstant.
19. Sumner, F. B. 1944. *Proc. Nat. Acad. Sci.,* 30 : 285–294.

Contribution No. 247

FIG. 1. Gelidium cartilagineum, the true "agarweed."

FIG. 2. Gracilaria confervoides, used for a time.

America's Agar Industry

PART I—Story of a raw material. It gives history and technology of agar and will leave you with a better understanding of product

By C. K. TSENG, Scripps Institute of Oceanography, La Jolla, Calif.

WHAT is agar? The U. S. Pharmacopoeia, ed. 12, 1942, defines it as "the dried mucilaginous substance extracted from *Gelidium corneum* (Hudsons) Lamouroux and other species of Gelidium (Fam. Gelidiaceae) and closely related algae (Class Rhodophyceae)." Similar definitions appear in various standard works, and, as a whole, seem indefinite, tending to include carrageenin and other red seaweed extracts.

The writer (Tseng, 1944*a*) has proposed a more precise definition: "the dried amorphous, gelatine-like, nonnitrogenous extract from Gelidium and other red algae, being the sulphuric acid ester of a linear galactan, insoluble in cold but soluble in hot water, a dilute neutral solution (1 to 2 percent) of which sets, upon cooling, to a firm gel solidifying at 35 to 50 deg. C., and melting at 90 to 100 deg. C."

Because of the lack of present knowledge concerning the chemical structures and physical properties of the various closely related hydrocolloids from red seaweed sources, any definition proposed now can only be tentative.

How is agar made? Agar is a very complex polysaccharide which occurs as a cell-wall constituent in agarphytes, such as *Gelidium, eucheuma* and *gracilaria*. Insoluble in cold but soluble in hot water, it easily can be extracted by boiling the seaweeds in water, congealing the solution by cooling, cutting the gel in whatever form wanted, freezing it by natural or artificial means, and finally thawing and drying it in the sun or by artificial heat. Freezing and subsequent thawing free the agar from salts and other water-soluble impurities originally present in the agar gel and produce a pure agar with rather low ash content.

For ages the sweetened and sometimes flavored agar gel has been used in China, Japan and the East Indies as a dessert. It was, however, in the middle of the seventeenth century, presumably in 1658, when the process of purifying and dehydrating agar in its present form was accidentally discovered by a Japanese innkeeper, Tarozaemon Minoya. He happened to note one morning that some agar jellies which he had thrown outdoors, and which had evidently frozen during the night, had thawed and dried in the sun to become translucent, membranous, porous flakes. Thus, the basic method of making agar utilizing natural freezing, thawing and drying was evolved. It still is being used by the majority of Japanese agar manufacturers.

The history of the American agar industry is that of the industry in California, for even to date, more than 80 percent of American agar is made in the southern part of this state.

A Japanese, Chokichi Matsuoka, established the first agar factory in the Western Hemisphere. In the early part of 1919, Matsuoka and six other Japanese formed the first American Agar Co. with a factory in Tropico (now Glendale), Calif., starting commercial production in 1920. Being familiar with modern American industry, Matsuoka improved traditional Japanese agar manufacturing methods by substituting artificial freezing for natural freezing. He also substituted chlorine bleaching for sun bleaching. Although less laborious, it is questionable whether chlorine bleaching produces as good an agar as the natural sun-bleaching process.

Matsuoka (1921, 1923) took out two American patents covering the method of agar manufacture. In his first patent, he emphasized the use of Gloiopeltis in his process and only casually mentioned Gelidium as a substitute.

Gloiopeltis furcata, the species he presumably used, does not grow in southern California, where he obtained his raw materials, and it is quite definite that he started making agar out of *Gelidium cartilagineum* gathered from the San Pedro Breakwater. While Gloiopeltis does produce a valuable hydrocolloid, it does not contain any appreciable amount of agar, and has never been used as an agar raw material.

The first American Agar Co. failed, probably because the Matsuoka process still involved the use of too much hand labor to be economically successful in this country. In 1923, the company was purchased by an organization headed by John Becker, a California engineer, who organized the second American Agar Co., and, in the next few years, modernized the manufacture of agar. Using some conventional equipment, Becker modified and invented a few new units. He took out four patents (1929 *a-d*) covering a special combined congealer and sizer, a dewaterer for flaked agar, a special dehydrater and also his entire process of agar manufacture. Today, the process used here is essentially Becker's.

Being a pioneer, Becker seemed more interested in devising new equipment, to modernize the American agar industry, than in actually producing agar, although he did make 162,686 lb. of agar in the first four years of operation (Table I). But the company was not strong enough to stand the strain of the last depression, and it finally closed in 1933. In the same year, a former employee of the company, S. F. Corfield,[1] established a small factory in National City, Calif., under the name, United States Agar Co. The agar produced by this and another small company in the years 1934-38 was reprocessed principally from Japanese agar, which was then so cheap[2] that it was no longer profitable to process agar in California, even with the relatively cheap Mexican Gelidium. The small United States Agar Co. eventually became the nucleus of the present American Agar and Chemical Co., now located in San Diego, the largest agar factory in the Western Hemisphere, with a production comparable to that of the larger agar factories in Japan. Most of the raw material for this factory comes from Mexico and the balance from Laguna, San Pedro and Redondo, in southern California.

TABLE I—U. S. Production of Agar and Imports from Japan.

Year	U. S. production (pounds)	Year	U. S. production (pounds)	Imported from Japan (pounds)
1923	7,755	1934	1,802	.....
1924	7,281	1935	8,061	.....
1925	117,773	1936	data not available	.....
1926	29,877	1937	21,208	704,000
1927	.....	1938	7,170	589,000
1928	22,797	1939	8,098	497,000
1929	5,140	1940	24,000	635,000
1930	44,895	1941	52,000	597,472
1931	28,395	1942	110,054	.....
1932	10,009	1943	165,954	.....
1933	41,557	1944 (Jan.-Aug.)	113,762	.....

*Production output figures for 1923-1938 and first nine months of 1939 are from U. S. Tariff Commission report (1941). Production data from 1940 were supplied by present agar manufacturers. No records are available of Matsuoka's agar production from 1920-1923.

Industry of Today[3]

When the WPB agar freezing-order was issued (Feb., 1942), there was only one agar factory operating in the United States, with an output of approximately 4,000 lb. per month. In September, when the agar-freeze order was revoked, this company was producing some 12,000 lb. per month, and in the meantime three other smaller companies were formed, although one of them has never produced agar. One of these is Agar Products Co. (Los Angeles, Calif.), which formerly used crude imported Japanese agar. When this source was lost to them, they found it possible to obtain their raw material from nearby regions in the Pacific Ocean. This changeover occurred in 1942, and in November, 1943, the production output was 1,800 lb. per month. The Pacific Agar Co., Whittier, Calif., started agar production in June, 1943, and is now producing about 1,200 lb. a month. A small factory at Orange was active in agar production only for a short while, and probably produced no more than 2,000 or 3,000 lb. All in all, the total American Gelidium agar production during the period when agar was frozen by WPB amounted to about 364,770 lb., about 87 percent of which was produced in the San Diego factory.

The increasing demand for agar also stimulated the growth of this industry in Mexico, the source of most of the agarphyte supplies for California factories. Two new factories are reported as operating here, and the larger of the two has an estimated maximum monthly capacity of 4,000 lb.

Eastern scientists and industrialists also became interested in agar production because of the shortage. Investigations by Humm (1942) showed that another agarphyte, *Gracilaria confervoides*, is present in commercial quantities in the vicinity of Beaufort, N. C. While there is still some controversy as to whether this agar is as good as the Gelidium-agar for preparing general bacteriological culture media, there is no doubt that it will serve most, if not all, purposes in the food industries. According to Humm's recent reports (1944), there are three com-

[1]Thanks are due to S. H. Corfield for supplying information regarding the history of the American agar industry and the present process.

[2]In 1933 the average price for imported Japanese agar was 49 cents per pound. However, during 1934 a large consignment of Japanese Kobz No. 1 agar sold for the low price of 40 cents per pound.

[3]Thanks to S. H. Corfield, L. K. Small and H. H. Selby of the American Agar and Chemical Co., E. S. Moorhead of Agar Products Co., M. E. Kirkwood of Pacific Agar Co., and American Chlorophyll, Inc., for figures on their respective production data and other pertinent information concerning the agar industry.

panies on the Atlantic Coast now actively engaged in the commercial production of Gracilaria agar. The most active concern, which is located at Beaufort, is producing about 3,000 lb. per month. Another, located at Scituate, Mass., produced some agar in the early part of this year, also using the Beaufort agarphyte, but it has temporarily stopped making agar while experiments are being pursued on a new method of manufacture. The third concern is located in New York, N. Y., presumably utilizing Florida Gracilaria for its agar extraction, but it has not as yet put any agar on the market.

EDITOR'S NOTE: *Part I of this article on agar is principally in the nature of an introduction. Other parts to follow will cover the subject thoroughly to give a complete story of agar.*

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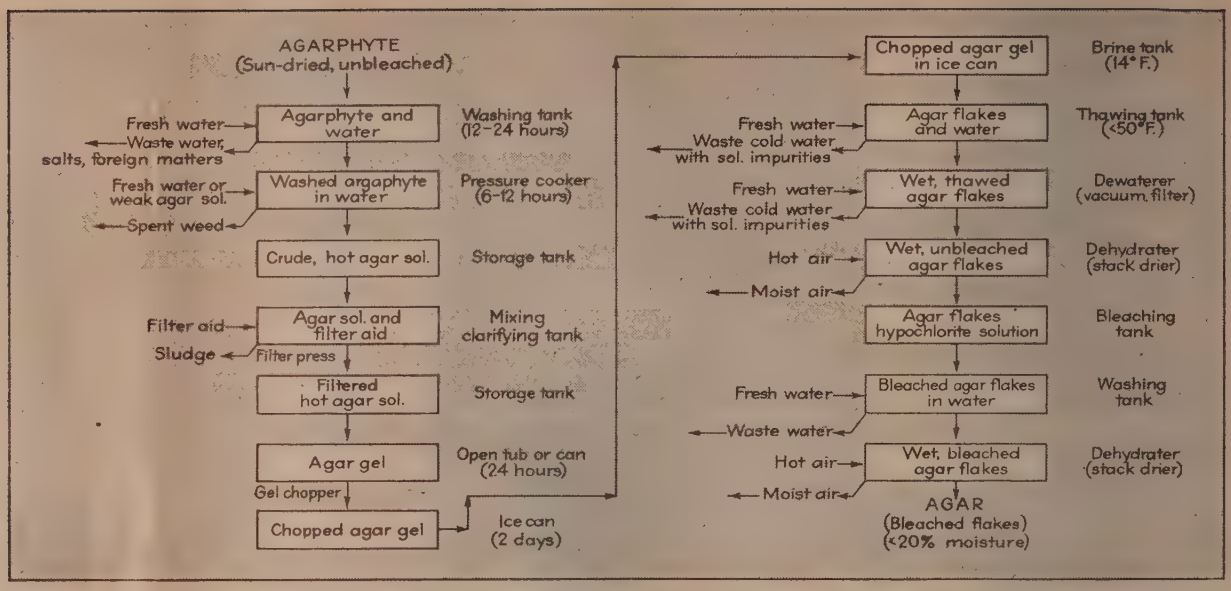
PART II—Sources of the agarphytes, methods and costs of harvesting, and details of the manufacturing process are given here. A flow diagram illustrates the process

MOST important of the American agarphytes is the maroon-red seaweed *Gelidium cartilagineum*, which is the true "agarweed." While it grows quite well in the Monterey region of central California, it is found in commercially harvestable quantities only in southern California and Baja California (Mexico), between Point Conception in the north and Magdalena Bay in the south. Reported to grow more than 4 ft. tall in extreme instances, the plant is generally under 3 ft. in height, and is considered harvestable when it reaches 18 in. Unlike the giant kelp, *Macrocystic pyrifera*, which grows in extensive beds, the Gelidium is generally found in small concentrations, localized on the top, or at the edge of rocks in places where the tidal current is strong.

Two other species of Gelidium have been used occasionally in the agar industry, *Gelidium nudifrons* and *Gelidium arborescens*, which, because of their thin and hair-like filaments, are called "hair-agar." These plants grow in bushes to about 3-ft. height in deep water and must be harvested by submarine divers. While slightly inferior, both plants are considered good agar sources. Due to their sparse growth, they seldom are found and usually are mixed indiscriminately with the principal agarphyte in the drying operation.

In California, *Gracilaria confervoides* was used in agar processing for a short time, but this variety is not being harvested on the West Coast at present (Tseng, 1944 *b*). In the East, however, the Gracilaria agar industry is growing rapidly, and last year's production, up to and including August, has reached 25,000 lb. Prior to this period, there was from 1,000 to 1,500 tons of green *Gracilaria confervoides* gathered near Beaufort between Aug. 1, 1943, and Jan. 1, 1944 (Humm, 1944). This was estimated as equivalent to 150,000 to 200,000 lb. of dry Gracilaria, which would yield approximately 50,000 lb. of agar. According to Humm, commercial quantities of this variety also have been located in the Indian River (Florida).

Diver going over side of boat to bring up agarweed. He carries a "basket" in which to put his harvest. One diver can gather as much as 1½ tons of Gelidium a day.



Flow diagram of the American process of agar manufacture, as used in California. The bleaching part of the process is used by only one concern.

Gracilaria confervoides grows in an entirely different environment than *Gelidium cartilagineum*. It prefers sheltered bays, especially near river estuaries, where the water is shallow, nitrate and phosphate contents of the water high, and water movement very sluggish. Harvesting is not so difficult. It is done at high tide by raking from a boat and at low tide by hand picking. One man easily can rake a ton of fresh Gracilaria during low tide. A ton of sun-dried Gracilaria is worth an estimated $120, but it requires 7 tons of the fresh plant, as compared to 3 tons of fresh Gelidium, to produce 1 ton of sun-dried material.

Harvesting

Gelidium is harvested by divers in California. Working in shallow depths, they hand pick the plant. Raking is rarely done in this region, being possible only when the water is extremely calm and when the Gelidium grows near the surface. Before the war, a crew of Japanese harvesters, experienced in raking seaweeds, gathered tons of this agarphyte from San Pedro Breakwater.

Agar diving boats usually are small (about 26 to 30 ft. long). They are equipped with a compressor and heavy rubber hose to supply air to the diver and ordinarily are manned by a crew of three: boat operator, diver and life-line tender.

As the Gelidium grows only in relatively small concentrations, mapping its location is impracticable. Agar divers, therefore, have to search for favorite spots where there is a good growth. Gelidium growths are readily noticeable to experienced divers because of the perpetual presence of the bryozoan Membranipora. Experienced agar harvesters also claim that there may be good growths of Gelidium wherever the "goldfish" garibaldi is found.

Working around the edges and the slanting surfaces of rocks in places where the water generally is turbulent and its movement is fast, agar divers have to crawl from one rock to another, occasionally holding to large kelps for support. The diver carries a basket made of small ropes into which he puts the agarphyte as he pulls it from the rocks. When the basket is filled with 60 to 70 lb. of agarweed, the life-line tender pulls it to the surface and lowers an empty one. Working during the morning, when the sea is calm, an experienced diver remains under water for one to two hours, then comes up for a rest period. Divers average four to six hours a day in underwater work, and under best conditions, a diver can harvest as much as 1½ tons of fresh Gelidium a day.

Most divers have to furnish their own suits, which last for approximately 20 divings.

Agar harvesters operate under two systems in southern California: (1) The agar company furnishes the facilities and pays the harvesters $85 per fresh ton. The company takes care of drying, baling and trucking to the factory. Earnings of the boat crews generally are divided into five shares, the diver getting three and the boat operator and life-line tender one each. Boat maintenance and operating costs are taken care of by the company. (2) The crew provides the boat, and the members harvest, dry, bale and sell the agarweed. Of the proceeds, the diver gets half, the boat operator and life-line tender one-sixth each, and the remainder is allocated to boat maintenance. Current prices for a ton of sun-dried Gelidium range from $350 to $400, and it requires about three tons of fresh "agarweed" to make a ton of sun-dried material.

Since diving operations are carried on in rather shallow waters (15 to 30 ft. deep), underwater work is done only when the water is calm and without strong ground swells. In southern California, most diving is done during the summer and fall. There are, on the average, 100 to 120 days during the year when the ocean is calm enough. May to November is the most favorable period.

The American Process

The present process of manufacturing Gelidium-agar in America is nearly the same as that devised by John Becker. Bleaching of agar with hypochlorite is done, as present, only by the San Diego concern. This process is costly, and while it improves the color, some agar manufacturers are uncertain as to its effect on gel strength.

The first step in processing the sun-dried, unbleached Gelidium is a thorough washing and soaking for

12 to 14 hours. The ratio of fresh water added to the agarphyte is largely dependent upon its quality—usually 1 gal. to a pound. The material is then transferred to pressure cookers, or digesters, and heated by steam at a pressure of about 15 lb. per square inch (a few plants use open kettles). It is cooked for 6 hours in a dilute agar solution obtained from the third and final cook. The partly spent agarphyte receives two more extractions, 8 and 12 hours, respectively, before being discarded as waste.

The extract is then clarified with filter-aid and filtered through an ordinary filter press. The clarified solution is poured into open tubs, where it gels firmly in about 24 hours at room temperature. The gel is fed through a chopper, dropping into ice cans (100-lb. capacity), which are moved into the freezing rooms and held for about two days at 14 deg. F. Taken from storage, the frozen agar gel is thawed in tanks at approximately 50 deg. F., then fed into the "dewaterer." An ordinary rotary filter, this machine retains wet agar on the screen and, by means of suction, removes the washing water containing soluble impurities.

The purified agar flakes, containing about 90 percent moisture, are fed into a stack dryer where a hot air blast (215 deg. F.) holds them suspended until they dehydrate to about 35 percent moisture content. Then they are light enough to float over the top of the stack and into the down-pipe. This pipe discharges the flakes into a tank for bleaching in a 1 percent sodium hypochlorite solution at room temperature. After the excess sodium hypochlorite is reduced by a sodium sulphite solution, the bleached agar is thoroughly washed and finally dehydrated in the stack dryers to about 20 percent moisture.

Agar intended for use in some food products or in culture media is fed through a swing-hammer mill equipped with a suction fan and cyclone collector. About 35 percent of the finely ground agar will pass through a 100-mesh screen, the remainder through a 60-mesh one. Estimates indicate a loss of about 10 percent from this powdering process.

Improvements Made

The present process of agar manufacture is essentially the same as the one described and illustrated in detail by MacKinnon in FOOD INDUSTRIES (March, 1930, page 123). There are, however, certain improvements. In the original Becker process, a special combined congealer and sizer was used to automatically cool and gel the solution. Then the solidified gel was extruded in appropriate sizes. However, Corfield found that holding or aging the material 12 to 24 hours during the period of gelation produced more and better agar. The present process eliminates the automatic congealer and substitutes the old method of cooling and solidifying the agar solution in open tubs or cans at atmospheric temperature, a practice that is now being followed by all of the agar factories in California.

In the original process, standard ice cans with a capacity of 300 lb. were used. But freezing was not homogenous in cans of that size, and the central portion of the block was not always completely frozen within two days. Therefore, a thinner can with a capacity of only 100 lb. was adopted.

Formerly, activated carbon was used in the mixing and clarifying tank before filtration to decolorize the agar. It was found that unless especial care was taken carbon particles would pass through the filter and eventually appear in the finished agar flakes. Decolorization by carbon was therefore discontinued, and hypochlorite bleaching was introduced at a later stage in the process.

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PART III—Agar may be used to advantage in some bakery and dairy products and in candy, jelly, canned foods and other items. It is used to give bulk and as a suspending, stabilizing, thickening or gelling agent

THE value of agar lies in its strongly hydrophilic colloid and high gel-strength qualities. It is used where bulk is wanted, or where a suspending, stabilizing, thickening or gelling agent is desired. The author (Tseng, 1944) has estimated the annual consumption of agar in the U. S. in normal times, and the figures, broken down by type of use, are given in Table I.

Although the Chinese and Japanese have used agar as a food in a variety of ways, its chief use in America is as a food adjunct. In the early days when agar was first introduced here, it was erroneously thought to be highly nutritious food. In fact, according to Saiki (1906), some agar manufacturers claimed that "Its food value is more than double that of an equal weight of eggs or beef-steak." However, researches made by Saiki (1906) and others, showed agar to be imperfectly assimilated by the human body and, consequently, not nutritious. This is due to the absence, in the gastro-intestinal tract, of enzymes capable of breaking down the extremely complicated polysaccharide found in agar. Recently, Nilson and Schaller (1941), experimenting with the growth of male albino rats bred on agar, concluded that the apparent digestibility coefficient of the nitrogen-free extract of agar was about 28 percent, but that they grew very well on a partial agar diet. The good effect of such diet is due probably to the supply of bulk, rather that the actual nutritive value contributed by the agar.

Roughage

Since agar is a nonnutritive food, its incorporation into various kinds of breakfast and "health" foods, as well as in bakery products, merely supplies bulk for a wholesome diet. This problem of bulk supply is one that only civilized men, accustomed to highly refined food,

have to consider. And it is for this purpose that agar has its most logical and valuable place in the human diet.

Bakery Products

The use of agar in bakery products also serves to increase bulk. There are so-called low-calorie breads or biscuits specially made for obese patients in need of reducing, and yet who must satisfy their desire to eat enough food. A patent was granted to Keyser (1916) for making crackers, wafers, cookies and other forms of biscuits containing agar, for people troubled with constipation. Keyser mixed agar in a "dry" dough, and after baking, the finished product contained ungelatinized agar. For the same purpose, a special "Agar and Oil Wafer" was made by a Cincinnati, Ohio, company. These were chocolate wafers, each containing a teaspoonful of mineral oil and agar, and were recommended to be taken with meals. The oil and agar, released during digestion, mix with waste materials in the lower intestine, and provide an aid to elimination. An analysis on "Agar-Bran Biscuits" was made by Bailey (1929) who found they were relatively low in protein and that their carbohydrate was very largely unassimilable. Because of its excellent moisture-retaining ability, agar also is added to some types of bread and pastries to keep them from drying out too readily. There also are special breads for diabetics in which the starch is removed and replaced by agar.

Dairy Products

In the manufacture of frozen dairy products, such as sherbets and water ices, agar is used as a stabilizer. It makes these products smooth and holds down the overrun by preventing the drainage of unfrozen sirup from the product in the hardening room. Unlike gelatine, agar acts quickly, and aging of the product is unnecessary. However, it has low whipping ability, so gums, which are better in that respect, must be added. Dalberg (1926) recommended 0.2 percent agar, together with 0.4 percent gum tragacanth or high-grade India gum for ices, and with 0.2 percent for sherbets. The high cost of agar in recent years, however, has prevented its wider and more general use in this field. Because of its low overrun and poor whipping qualities, agar is not recommended as a stabilizer in making ice cream.

Agar plate, illustrating use of this seaweed product in bacteriological culture. In this case, trilaurin and an indicator, neutral red, were added to agar, and certain anaerobic bacteria grown on it. The darkening was due to the action of the liberated lauric acid on the indicator.

Table I—Annual Agar Utilization
(Estimated)

	Pounds
For laxatives	100,000
Microbiological and culture media	100,000
Bakery industry	100,000
Confectionery industry	100,000
Dental impression molds	75,000
Meat packing	50,000
Emulsifiers	50,000
Cosmetics	25,000
Miscellaneous uses	50,000
Total	650,000

In the manufacture of cream cheese of the Neufchatel type, agar serves to reduce the tendency of the cheese to exude when at warm temperatures, to provide slicing qualities and to produce a firmer body (Dalberg, 1927). While its use has the disadvantage of requiring a higher temperature to dissolve it than if gelatine is used, agar has a decided advantage over the latter in improving the texture of the cream used in the cheese (Marquardt, 1930). Powdered agar of the highest grade is recommended for cheese, and the quantity used in this product varies from 0.2 to 0.1 percent.

As a stabilizer and thickener, agar also is used in such drinks as malted milk and acidophilus milk. A patent was granted Lecomte (1911) covering the use of agar to prevent the separation of fat in cream or milk. In preparing the so-called "Imperishable Milk," North (1924b) separated the solids from the cream, which was then emulsified with agar. his process took away the "foods" for the growth of putrefying bacteria, thus helping to keep milk fresh. On the same principle North (1924a) was granted another patent on "imperishable butter." For these purposes 0.5 percent agar was used.

Jelly, Candy and Other Food Preparations

At the time agar was introduced to America and European countries, during the middle part of the last century, it was originally intended to serve as a gelatine substitute in making fruit and vegetable jellies. Having a much higher strength, about eight times or more than that of ordinary gelatine, it is a more economical gelling agent. Unlike gelatine, it does not require refrigeration to form a firm jelly, even in tropical countries, and it requires less time to make an agar-based jelly. Orthodox Jews prefer jellies made of agar to those made of gelatine, which is of animal origin. And compared with pectin, agar has the advantage of not requiring sugar to make jelly.

In the manufacture of confections, agar is used in making jelly candies and marshmallows. Jelly, for this purpose, is made by adding as little as ¾ to 1 percent to the mix. It also tends to make the final product easier to cut.

Agar is used extensively in making icings and various types of custard-like preparations and has been used in mayonnaise (Hart, 1937) although legally such a product should not longer be so called. It is also used in preparing various kinds of salad dressing and it is reported to be used as a sausage casing. A patent using agar, alginate and pectin as stabilizer and bulk producers was granted to Washburn (1932).

Canning, Preservation

Meat canners use agar both as a thickening and as a gelling agent, especially for the softer types of meat and fish which might fall apart during subsequent handling after canning. The constituents of certain fish, such as herring, attack metal cans, and produce a detinning action, blackening the contents of the can and rendering it unsalable. Agar, combined with such fish, eliminates this chemical action (Gamage, 1922). It retains its gelatinizing power to a greater extent than animal gelatine when subjected to high temperatures and pressures necessary in processing meats or fish, and is also widely used in canning chicken.

Matsuoka (1924) was granted a patent for making dehydrated and powdered fish extract with agar for use in soups, gravies or other food flavoring preparations. Another patent was granted to Nishio

924) for a similar process, ex-
ot that the solidified mass of
n extract and agar was allowed
mold until a hard product was
tained. While such products
ght be to the Oriental taste, they
not appeal to the American
ate and are no longer made.

Culture Medium

The most important service that
ar renders to mankind is as a
cteriological culture medium, al-
ough the amount used for this
rpose is relatively small. In the
ited States normally about one-
th of the total utilization of agar
is used for this purpose.

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NUTRITION AND GROWTH OF THE CALIFORNIA BAY-MUSSEL (MYTILUS EDULIS DIEGENSIS)[1]

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TWO FIGURES

The nature of the food and the rates of growth of the California sea-mussel (Mytilus californianus) at different ages, different seasons and under various environmental conditions during four successive years have been reported by Coe and Fox ('42, '44) and Fox and Coe ('43). The conclusion that organic detritus ordinarily supplies a far greater part of the mussels' nutrition than the combined phytoplankton and zooplankton is of sufficient importance to warrant a reinvestigation of the subject on some other species of mucus-feeding bivalve under the same environmental conditions.

The opportunity of making such a study on another species of mussel has been provided by the recent establishment of large colonies of the California bay-mussel (Mytilus edulis diegensis) on the piles at the Scripps Institution. In the autumn of 1944 this subspecies had become abundant at various localities from San Pedro to the Mexican border, not only in the bays and inlets which are its usual habitat but also in suitable situations on the open coast. Because of the coastal currents which average about 4 to 5 miles per day, north or south, the free-swimming larvae are subject to a wide distribution during the larval period.

In order to determine their rates of growth the experimental animals were kept in a wire-screened box divided into compartments and immersed in the sea at a level slightly below the surface during periods of low tide. The box contained at all times representatives of various sizes and ages, usually with about twenty individuals of each of five to seven sizes with an average difference of about 10 mm. in length, making a total of more than 100 individuals. They were measured at monthly intervals of 30 days.

[1] Contributions from the Scripps Institution of Oceanography of the University of California, New Series no. 248.

Since it was observed at the beginning of the experiment that young individuals increase in length more rapidly than those which are several months of age it was necessary to have in the box individuals of approximately the same ages or sizes at all times. This necessitated the addition of young individuals at the time of each of the monthly measurements and the discarding of an older group. In this locality reproduction occurs at all seasons of the year, but particularly in late autumn and early spring, and young individuals are nearly always available. The food supplies present in the water throughout the year and the processes of digestion were studied by frequent examination of the contents of the digestive canal and the feces.

For assistance in making these studies the writer is indebted to Dr. Bradley T. Scheer, Dr. Fritz Haas, Prof. and Mrs. C. L. Hubbs, Miss Harriet Dunn, Mr. Carl Johnson, and particularly to Prof. Denis L. Fox for his friendly cooperation in all aspects of the investigation.

RATES OF GROWTH AT DIFFERENT AGES

The mean increase in length under favorable conditions reaches a maximum during the second and third months after completion of the free-swimming stages and decreases rather rapidly thereafter. When the young individual becomes attached in spring or summer it commonly attains a length of 7–10 mm. during the first month, increasing to 19–24 mm. in the second month and to 30–36 mm. in the third month. An occasional individual may gain as much as 16 mm. in a month. It must be noted however that the monthly rate of increase during the winter is only about half as great as in summer (fig. 1). Computing the average rate for the entire year, it is found that the monthly increment for the first 12 months after attachment are approximately 7, 10, 10, 9, 8, 7, 6, 5, 4, 4, 3, and 3 mm. respectively. This represents a total of 76 mm. for the year.

An average increment of less than 2 mm. per month, or a total of 20 mm., may be expected during the second year, bringing the length to 96 mm. This increase is thus but little more than one-fourth as great as in the first year. Individuals about 100 mm. long gained an average of only 3 mm. in 8 months after being placed in the experimental box. The largest individual seen by the writer measured 108 mm. in length.

The decreasing rate of growth with increasing age and size is well illustrated by taking the average increment in length of each of the seven groups during the 4 months August through November, 1944.

During this period the average increase per month for each group was as follows:

GROUP		AVERAGE INCREASE PER MONTH
	mm.	*mm.*
1	11–20	11.3
2	21–30	11.1
3	31–40	9.9
4	41–50	8.0
5	51–60	5.9
6	61–90	2.8
7	91–103	0.75

The maximum size at the age of 1 year in 1943–1944 was 78 mm. and the average about 66 mm.

Since the rate of increment was so small in groups above 60 mm. in length and so irregular because of the influence of the reproductive processes, only those groups between 11 and 60 mm. have been used in obtaining the index of growth for each month. These five groups, differing from each other by 10 mm. in length, naturally fall into two

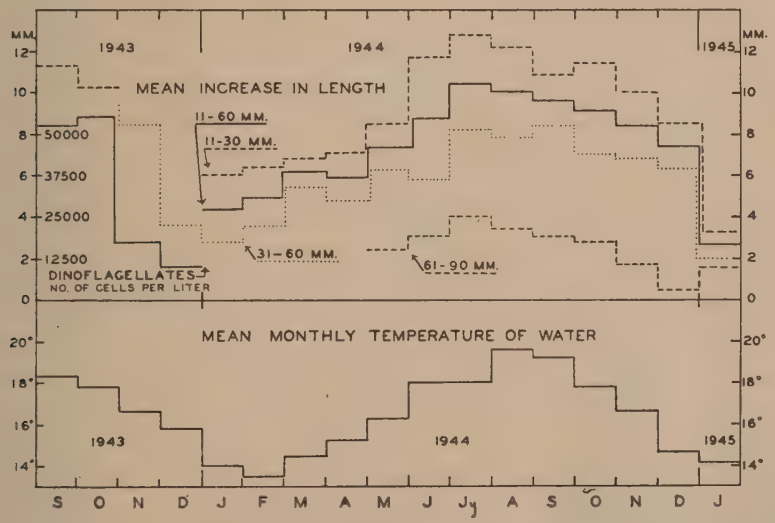

Fig. 1 Monthly increment in mean length of bay-mussels in experimental boxes from September, 1943, to January, 1945. The three series, 11–30 mm., 31–60 mm. and 61–100 mm. are indicated separately and show the decreasing rate of growth with increasing age and size. The correlation of growth rate with water temperature is rather close except in August. The increment in December, 1943, was less than half as great as in the corresponding month of 1944, due in part to storms and heavy seas in the former month. A similar sharp decline in the growth rate occurred in January, 1945, apparently for the same reason.

The correlation of growth rate with the abundance of dinoflagellates is considered as indirect, since the living dinoflagellates do not contribute directly to the nutrition of the mussels.

series. One of these contains the two most rapidly growing groups, 11–20 and 21–30 mm. in length and the other the three groups 31–40, 41–50, and 51–60 mm. long, in which, as previously stated, the rate of increment is progressively less. The index of growth is considered as the average of the means of each of these two series. By this method of treatment the numbers are sufficiently large to avoid individual fluctuations in rate (fig. 1).

The average monthly increase in each of these two series for the last 4 months of 1943, for each month of 1944 and for January 1945 is shown in figure 1, together with the averages of the two series. For several of the months the increase in the groups above 60 mm. is also indicated.

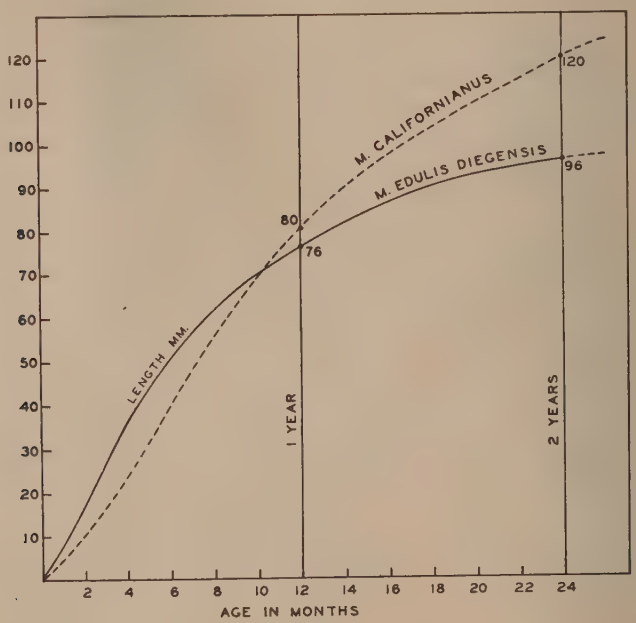

Fig. 2 Increase in length of bay-mussels in culture boxes during first 2 years of life as compared with the growth of the sea-mussel during the same period. The latter grows more slowly than the former during the first 5 months after attachment but more rapidly thereafter.

As compared with M. californianus kept under the same environmental conditions (Coe and Fox, '44) the growth rate of the bay-mussel is higher during the first 5 months after attachment but lower thereafter (fig. 2). At the end of the first, second and third years, individuals of the former species normally measure, respectively, about 80, 120 and 140 to 150 mm. in length, while those of the bay-mussel, as has been

stated, may reach a length of about 76 to 78 mm. in the first year and 96 mm. during the second year but the increase thereafter, as shown in figure 2, is very slow.

INFLUENCE OF TEMPERATURE ON RATES OF GROWTH

In this locality growth and reproduction of mussels and many of the other invertebrates continue throughout the winter, the difference between summer and winter temperature of the water being only from 6° to 8°C. The low of 14–15° in winter and the high of 20–22° in summer are both within range of the mussel's normal metabolism. Being situated on the open coast the storms and heavy seas prevalent at intervals during the winter are much more detrimental to normal activities, including growth.

As the graphs in figure 1 indicate, there has been a rather close correlation between growth rate and temperature of the water, with only three exceptions. Beginning with September, 1943, there was a continuous decline in the growth rate to a minimum in January, accompanying a continuously falling temperature (fig. 1). The sharp decrease in the growth rate during December of that year was presumably due in large measure to the rough seas which were prevalent at that time. During February the growth rates of both series increased, although there was a further decline in the temperature. With the rising temperatures from the beginning of March to the end of July there was a continuous increase in the growth rates of the younger series, although in both April and June the rates of the older series declined slightly. Following the maximum rate in July there was a continuous decrease in the averages of the two series throughout the rest of the year. There was an unusually sharp decrease in January, 1945, due to storms during that month (fig. 1). The rates in all groups declined in August, the month of highest temperature. Coe and Fox ('44) likewise found a decreased growth rate in M. californianus during that month in each of the 4 years of their experiment.

Although the increase in length of the group of old individuals, 61–90 mm., was much less than in the two series of younger animals, there was a similar correlation with temperature changes. The rates for this group likewise reached a maximum in July, followed by a continuous decline during the rest of the year (fig. 1).

NUTRITION AND GROWTH RATE

In their studies on the California sea-mussel, Coe and Fox ('44) found that the most rapid growth in that species took place as a general rule

in those months and in those years when large dinoflagellate populations were present in the water. It was evident however that the observed correlations were indirect, since no satisfactory evidence was found that living dinoflagellates can be utilized by the mussel. Even when ingested in large numbers they usually pass through the digestive canal without apparent change. Their disintegration products after death however add to the available detritus. The correlations mentioned are evidence that both the dinoflagellates and the mussels thrive under the same environmental conditions. A similar correlation was found in the bay-mussel (fig. 1).

The sea-mussel's principal source of food "consists of minute particles of organic detritus derived from the disintegration of the cells of all kinds of marine organisms, both animals and plants, supplemented by living and dead unicellular organisms of minute size, as well as by living and dead gametes. There is no evidence that organic matter in true solution can be utilized until after it has been changed into particulate form by the action of unicellular organisms" (Coe and Fox, '44).

In the bay-mussel particular attention has been devoted to this problem of nutrition by examining at frequent intervals throughout the year the stomach and intestinal contents and the feces. The conclusions stated above for the sea-mussel have in most respects been confirmed. Attention may again be called to the method by which the mussel secures its food. As with other similar feeders, a sheet of mucus is continually being secreted over the gills during the feeding process and through this the water drawn into the mantle cavity through the inhalent opening is strained. The particles suspended in the water are thereby caught in the sheet of mucus which is then drawn into strings by ciliary action. These strings with their contained particles are usually carried to the mouth. If the particles are too large or in excess of the capacity of the mussel for ingestion or are otherwise unacceptable, the laden mucus strings are rejected and cast out of the mantle cavity as pseudofeces. There seems to be no selection among these particles except as to size. Relatively large and spiny objects are prevented from entering the inhalent opening.

In this manner the mussel takes into its digestive system a vast assortment of suspended particles, both digestible and indigestible. In the latter group are almost invariably found particles of shells and sand, fragments of the cellulose walls of algae and empty diatom frustules, as well as such living and dead dinoflagellates and other microscopic algae as have cellulose walls which resist the action of the

enzymes in the digestive canal of the mussel. To be included among the indigestible substances also are all living cells and organisms which are too large for intracellular digestion.

Digestion is mainly intracellular and is accomplished principally by the phagocytic cells lining the digestive diverticula. These are supplemented by migratory phagocytes which enter the stomach and intestine and take into themselves selected food particles, including small diatoms. The engorged phagocytes then return to the lining epithelium. After freeing themselves of the indigestible constituents of the engulfed material they continue through the epithelium to the connective tissues, as Yonge ('26) has so fully described for the oyster. This has been confirmed by Graham ('31) for the razor clam and by Fox and Coe ('43) for the sea-mussel. A very small amount of nutriment may also be obtained by phagocytic cells on the surfaces of the gills and mantle. These may ingest nutritive particles and then return to the connective tissues of the body.

It is generally agreed that the only enzymes secreted into the digestive canal are amylase and glycogenase which are incorporated in the style and liberated into the stomach. Consequently neither proteins nor fats can be assimilated unless they are taken into the above mentioned phagocytic cells, either those lining the digestive diverticula or the migratory cells in the lumen of the stomach and intestine. They are then digested intracellularly by the respective intracellular proteases and lipase.

For these reasons only those living cells which are small enough to be surrounded by the cytoplasm of the phagocytic cells, either singly or in groups, can be digested. All others are discharged in the feces. After the death and fragmentation of the large cells however many of their disintegrated particles become available for intracellular digestion. In the living cells which are too large for intracellular digestion the stored carbohydrates are surrounded by protoplasm and are thereby protected from the action of the amylytic enzymes in the stomach. Such cells as do not die and become disintegrated may pass through the digestive tract without being injured. Proof that some of these are still viable and capable of normal reproduction may be obtained by removing the rectal contents, with proper precaution against contamination, and placing them in sterile nutrient solutions.

The relative importance of the living phytoplankton, including algal spores, dinoflagellates, diatoms and other algae, and bacteria, as compared with the detritus in the nutrition of pelecypods has been the subject of much discussion. It is highly probable that this relation

varies with the species and with the available supply of each of the two groups of nutritive substances. Field ('22) and Coe and Fox ('44) have emphasized the importance of detritus for the nutrition of mussels, Churchill and Lewis ('24) for fresh-water mussels, and Blegvad ('14) and others for oysters.

In their studies on the California sea-mussel, Fox and Coe ('43) concluded that the living phytoplankton available during the year, even if all of it could have been utilized, would have supplied less than one-fifth of the organic matter needed by that species for its growth and reproduction. This conclusion was reached by calculating the approximate weights of the dinoflagellates, diatoms and bacteria present in the surrounding water throughout the year, together with the total volume of water which a mussel of standard size would presumably filter during the same period. It was emphasized, however, that this was only potential food, and that only a portion of the ingested material could be assimilated. Furthermore chemical analyses showed that the dried feces contained approximately 30% of organic matter, including about 7% protein. These analyses support the microscopical examinations in proving the sea-mussel's inability to utilize a large proportion of the material which is ingested.

In the bay-mussel also the nutritive substances found in the digestive canal consist principally of: (1) phytoplankton, including algal spores, dinoflagellates, diatoms and other algae, and bacteria; (2) zooplankton, including flagellates, ciliates, tintinnids and other protozoans; (3) gametes and dissociated embryonic cells of invertebrates, including spermatozoa, small ova and dissociated particles of larger ova; (4) organic detritus, both that originating locally and that brought from a distance by ocean currents.

1. Phytoplankton

Both living and partially disintegrated dinoflagellates and diatoms are invariably present in the stomach and intestine of mussels brought directly from the sea but the numbers, both in the stomach and in the sea, may vary a hundred fold from one week to the next as various populations of these organisms are brought to the mussel beds by ocean currents.

Dinoflagellates. Most of the local dinoflagellates have cellulose walls and are much too large for intracellular digestion. For both of these reasons the intact cells are unassimilable and most of them are discharged in the feces without apparent change. It has been mentioned

in a preceding paragraph that the digestive canal is not provided with enzymes for the digestion of either cellulose or protein. Only the disintegration products of the dinoflagellates are potential sources of nutrition, the proteins and lipids by intracellular digestion and the polysaccharides by the enzymes in the stomach as well as by intracellular enzymes.

Diatoms. These organisms have long been known to contribute to the food supply of all mucus-feeding invertebrates, and artificial cultures of some of the minute diatoms have proved more successful for the rearing of larval invertebrates than any other material. They have been generally considered to be essential in the "fattening" of both English and American oysters. Nelson ('42) has emphasized the importance of certain species in the building of glycogen reserves and imparting a superior flavor. He clearly distinguished between the minute, assimilable forms and the larger spiny species, calling the latter "weeds of the sea."

Acting on the general belief that oysters accumulate more glycogen and become fatter in those years when the phytoplankton is more abundant, Loosanoff and Engel ('44) attempted to accelerate the process by supplying concentrated cultures of living cells of the minute green alga Chlorella, the diatom Nitzschia, the dinoflagellate Prorocentrum and the euglenoid Euglena. In most of these cultures the attempt was unsuccessful, however, for the higher the concentration the thinner the oysters became, since little or no food was ingested. The excess material clogged the gills and interfered with normal feeding. The conclusion was reached that those seasons and those localities having a relatively small amount of phytoplankton are best for the "fattening" of oysters. The question arises as to which, if any, of the four types of organisms, with the exception of Nitzschia, used in these experiments are actually capable of utilization by that species of oyster until after they have died and become disintegrated.

Only the small species of diatoms can be phagocytized by the mussel and these are so minute that it is estimated that more than 500,000,000 would be needed to provide 1 gram of dry organic matter. Fox and Coe ('43) calculated that the diatoms present in the water about the mussel beds during the year could if fully utilized supply only a small fraction of the organic matter needed by the sea-mussel for its growth and reproduction. By comparing the yearly growth rates of the mussels with the abundance of diatoms during 4 years, Coe and Fox ('44) found that the mussels grew most rapidly in the year having the smallest number of diatoms and least rapidly in the year when the numbers

were three times as great. In the bay-mussel the conditions are similar. During the year 1943 the water contained an average of 54,300 diatoms per liter. The rate of filtration, if about the same as in the sea-mussel, would have brought a 60 mm. individual 10,000 liters of water during the year. This water would have contained about 543,000,000 diatoms, but these would have provided the mussel with only about 1 gm. of dry organic matter even if they could all have been utilized. But, as already mentioned, most of those present in the water at that time were so large as to be unassimilable until after death and disintegration.

That minute diatoms are readily digested is shown by the fact that within 20 hours after the mussels have been fed cultures of small species the feces consist mainly of chloroplasts, with only a few intact cells.

Green algae. Many kinds of small algal cells are ingested but most of them have cellulose walls and are therefore not assimilable in the living condition. Spores of various unicellular and multicellular algae however are often available in vast numbers and are readily phagocytized by the cells of the digestive diverticula as well as by the migratory phagocytes. At certain periods they presumably furnish an abundant nutrition since they contain in assimilable form all the organic nutritive requirements of the mussel.

Bacteria. These are constantly being ingested whenever the mussel is feeding and are doubtless readily assimilated. The water is estimated to contain an average of 45,000,000 bacteria per liter, but they are so minute that Fox and Coe ('43) calculated that 10^{12} cells would yield only about 0.05 gm. of dry organic matter. Hence they can constitute but a minute fraction of the mussel's nutritive requirements.

2. Zooplankton

A large variety of protozoans, including flagellates and ciliates are often ingested but not usually in large volume. Many of the flagellates are small enough for intracellular digestion but the ciliates are generally so large that only their disintegration products can be utilized. It may be repeated that the digestive canal of the mussel is not provided with the protease which would be necessary for the digestion of proteins.

3. Gametes and embryos of invertebrates

Spermatozoa from various invertebrates are at brief periods ingested in far greater numbers than the mussel can assimilate. Many of them are carried to the digestive diverticula where they are readily phagocytized. Others are assimilated by the migratory phagocytes

and doubtless furnish a highly concentrated nutrition. Small embryos, larvae and dissociated embryonic cells are often found alive in the digestive canal but only their disintegration products can be utilized. Where supplied in too great excess the surplus is discharged from the mantle cavity as pseudofeces. The seasonal growth rates of the sea-mussel were found by Coe and Fox ('43) to be correlated rather closely with the spawning seasons of the neighboring invertebrates, as well as with the periods when barnacle larvae were liberated in greatest numbers. That is also true of the bay-mussel.

4. Detritus

Examination of the stomach and intestinal contents, as well as the feces, invariably shows a large proportion of unidentifiable particles of organic matter which have evidently been derived from the disintegration of the cells of various plants and animals. This organic detritus is always present in the sea-water and on the surface of mud, sand and rocks. It soon forms a film on all solid objects immersed in the sea. If the objects are not poisonous or otherwise deleterious, bacteria are always present, followed by other sedentary unicellular and multicellular organisms.

Every plant and every animal which lives in the sea may sooner or later contribute its share in forming this detritus, both directly by its reproductive cells, waste products and dissociated cells and eventually by its entire body after death. The feces of both vertebrates and invertebrates, including those of the mussels themselves also contribute to the detritus considerable amounts of nutritive substances. The detritus may originate in the locality where it is used as food or it may be brought from a distance by ocean currents. Even land animals and plants may add their contributions through the run-off water. Part of the organic matter in the sea is in true solution but there is no satisfactory evidence that this can be utilized by the mussel and similar mucus-feeders until it has been changed into particulate form through the agency of unicellular organisms.

A large proportion of the ingested detritus consists of cellulose from the walls of algal cells and dinoflagellates. This cannot be utilized by the mussel because of the absence of suitable digestive enzymes. Only the cell contents which are composed of lipids, proteins, starches and glycogen contribute to the mussel's nutrition. For the digestion of these the mussel produces lipase, protease, amylase and glycogenase, respectively. The two latter are secreted into the style and liberated in the stomach, while the fats and proteins can be digested only within

the cells of the digestive diverticula and in the migratory phagocytes (Fox and Marks, '36; Fox and Coe, '43). The same enzymes were found by Yonge ('26, '35) in the oyster and by Graham ('31) in the razor clam.

The relative contribution of each of these four classes of foods to the nutrition of the mussel doubtless depends in large measure upon the periodic supply of each. During the winter months, when dinoflagellates, diatoms, zooplankton and gametes are least numerous, there is often a surplus of algal spores, while in the spring and autumn there is a great abundance of gametes of invertebrates. Detritus is constantly being formed locally, although in varying amounts, as well as being brought from a distance. Furthermore representatives of each of the four classes of food materials are present at all times and growth continues throughout the year. The feces indicate that these food supples are generally present in amounts far in excess of the mussels' capacity for assimilation.

Preliminary examination of the contents of the digestive canal and the feces of various other species of pelecypods, including Pecten, Tivela, Ostrea, Chione, Macoma, Donax and Tagelus, indicates that detritus is generally far more important than living microorganisms as a direct food supply. Most of the latter although ingested freely are more commonly utilizable only after their death and disintegration.

SURVIVAL IN AQUARIUM

Individuals of this species have lived for nearly a year in a large aquarium supplied with an abundance of running water but usually without making any considerable growth. During the first month a few individuals added 1 to 2 mm. to the length of the shell, after which no increase occurred. The water evidently lacks sufficient nutritive materials for normal metabolism, for individuals of the sea-mussel when kept in the same water but provided with an abundance of detritus and other substances grew about one-third as rapidly as others under normal conditions which had three times as many hours for feeding each day (Fox and Coe, '43). Examination of the aquarium water shows that it contains about the same microorganisms and detritus as the water in the sea but in much smaller amount.

The shells of the mussels remain open and byssus threads are secreted normally during the first few weeks. Food is ingested and feces discharged in small amount. Spawning may occur but is not usual. The tissues finally become thin and watery and lose more than half of their

organic matter, although there is no decrease in the weights of the shells.

Some marine invertebrates thrive better in the aquarium if the water is more fully aerated by being supplied from splash-buckets. Even by this method a group of twenty-six bay-mussels of the most actively growing sizes, 14 to 31 mm., made no increase in length during 4 months. All became thin and watery and several died during the fourth month.

SUMMARY

On the coast of Southern California the bay-mussel (Mytilus edulis diegensis) commonly reaches a length of 66 to 76 mm. at the age of 1 year after completion of the free-swimming stages and 90 to 96 mm. at the age of 2 years. Thereafter the rate of growth is very slow.

As compared with M. californianus under the same environmental conditions the bay-mussel grows more rapidly than the former during the first 5 months of life but more slowly thereafter.

Except for the interference by severe storms there is a close correlation between growth rate and temperature, although there was a decreased rate in August, the month of highest temperature. The rate is only about half as great in winter as in summer, even though the difference in average temperature between the coldest month in winter and the warmest month in summer was less than 6°C. in 1944–5. The growth is greatly impeded by storms and high seas.

For a portion of the year records of the abundance of dinoflagellates were available and they showed, as had been previously demonstrated for Mytilus californianus, a remarkably close correlation with the growth rate of the mussels, although the living cells contribute but little to the food supply. A less definite correlation was found for the diatoms.

Digestion and assimilation are mainly intracellular through the agency of the phagocytic cells of the digestive diverticula and migratory phagocytes in the lumen of the digestive canal. Similar phagocytes on the gills and mantle may aid to a very small extent.

Extracellular digestion is limited to the carbohydrates through the agency of amylase and glycogenase secreted into the style and liberated in the stomach.

Cellulose is indigestible; consequently such unicellular algae, including dinoflagellates, as have cellulose walls are unassimilable while living, athough their disintegration products after death are suitable for intracellular digestion.

Small living diatoms are readily phagocytized but the larger species pass through the digestive canal without apparent change. The number available during the year is insufficient to contribute more than a small percentage of the mussel's nutritive requirements.

Algal and animal reproductive cells and protozoa that are small enough for intracellular digestion are often important constituents of the diet. Larger cells are available only after death and disintegration.

The available supply of living phytoplankton and zooplankton combined which the mussel can both ingest and utilize during the year is far from sufficient to supply its needs for growth and reproduction; a large proportion of its nutrition is obtained from organic detritus derived from the disintegration of the cells of all kinds of marine plants and animals. The detritus may be of local origin or brought from a distance by ocean currents.

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Contribution No. 249

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OCCURRENCES AND ABUNDANCES OF MARINE PLANKTON DIATOMS OFFSHORE IN SOUTHERN CALIFORNIA[1]

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Diatoms are highly important microscopic plants living in water or on moist surfaces anywhere and almost everywhere in the world. As single-celled individuals very few of them are ever seen by the unaided human eye, but as colonies or aggregations of cells they are often visible as brown, slimy films or gelatinous coverings on submerged rocks or other solids in sea water along shore. In our domestic water supplies they are more familiar to taste and smell than to sight. In any environment it is probable that they serve as food for many different kinds of animals, mostly small, that they help prepare a foothold for plants slightly larger, that they contribute materially to the series of physical and chemical changes occurring in Nature, and that they often indicate by the character and vigor of their life processes many features of these changes which might escape notice under direct observation.

Although diatoms were known more than sixty years ago to exist afloat in sea water and although special studies of their occurrence had been made off the New England coast and in Puget Sound nearly fifty years ago, these pelagic plants had received little attention in Southern California prior to 1917 when regular series of collections were made near San Diego as part of a preliminary survey of the "fertility of the sea." Although the equipment used then by the Scripps Institution was cumbersome and the methods crude, the resultant data were informative and stimulating. For example, it was found that large populations existed at times at distances more than one hundred miles from shore, that many genera and species were represented in these populations and that populations differed extremely in density and composition in differing times and places.

Not until the summer of 1926 did the operations at sea acquire a truly definitive basis. In that year two fixed stations, located respectively five and ten miles to seaward from the Scripps Institution of Oceanography at La Jolla, were selected and occupied at semi-weekly intervals for about six weeks. That frequency was sufficient to aid materially in improving understanding of trends of changes of populations away from shore. At the same time certain changes in methods of operation greatly increased the accuracy of observations while enabling far greater speed and ease in procedures. Fundamental and essential in this improvement was the introduction of use of the Allen Closing Bottle for obtaining a measured sample of sea water combined with the use of a small filtration net for concentration. Notable

[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 249.

results of these improvements were numerical records for comparison of populations not only at the two stations but also at levels at ten-meter intervals from the surface to sixty meters. Thus it was found that populations differed in density and component species at the two stations and in the rate and quality of changes in these characteristics.

Notwithstanding the dependability and success of improved procedures no progress was made in observations on populations of diotoms offshore until 1938 when the acquirement of a suitable ship and the organizing ability of Director H. U. Sverdrup enabled the inauguration of series of systematized cruises on carefully selected lines, some of which extended more than 200 miles to seaward. In 1938 these cruises were bi-monthly, beginning in February and covering four lines (the northernmost extending southwest from about San Luis Obispo and the southernmost extending southwest from about San Diego). In 1940 they were bi-weekly for twelve weeks from March, and the northernmost line extended nearly west from Port Hueneme. In 1941 they were monthly from March and the southernmost line extended south of west from about Ensenada, Lower California.

Although the time intervals in the bi-monthly cruises of 1938 were much too large to permit identification of most of the sequential relationships of diatom populations or proper evaluation of the phenomena accompanying their presence, absence, or composition, they were small enough to show some seasonal actualities at selected stations in a particular year and to suggest a number of probabilities concerning normal existences of such populations in the region. Apparently most reliable among these showings were a few geographical items, first, superior production on the line out from San Luis Obispo. Second, evidence of good productive possibilities in the line out from Santa Barbara (especially near Santa Cruz and Santa Rosa Islands) and the line out from San Diego. Third, low production in the line out from Oceanside. Fourth, low production in all lines at stations farther offshore than the edge of the "continental shelf." Fifth, extreme differences in abundances at individual stations in any line. Not least important was the showing that catches from levels below 50m were rarely equal or superior in size to some at higher levels. In the 1938 cruises the surface level appeared to be fairly representative of abundances at most stations although leading less often than the 30m and 50 m levels. Seasonal distribution of station aggregates (all levels combined) conformed fairly well to the year pattern observed in series of daily catches (for the whole year) at inshore stations at La Jolla and Pt. Hueneme. Representatives of 35 genera and 84 species were observed but only four species were outstanding, i.e., *Chaetoceros compressus* Laud., *C. debilis* Cl., *C. radicans* Schütt. and *Nitzschia seriata* Cl. However, it should be noted that the ranking of species by abundances differed strikingly from the ranking by occurrences (number of times recorded), e.g., *C. radicans* was first in total numbers of cells for the

six cruises but only sixth in times recorded. A strange and totally unexpected relationship was noted in the fact that filamentous species such as *Thalassiothrix longissima* Cl. and Grun. were recorded more frequently than any of the setose species such as *C. radicans*. The full report on the cruises of 1938 is being published by the University of California Press.

In the 1940 series the semi-monthly frequency of the observations made it reasonable to attempt some detailed analyses and interpretations of relationships of diatom populations which had not been possible before that time. Because of the remarkable results of this treatment it was decided to prepare for publication the general section of the report (dealing with abundances only) in order to find time for an early examination of general aspects of the data for 1941. The primary reason for this decision was the fact that the bi-weekly data for 1940 provided convincing evidence that a striking geographic condition existed which was scarcely discernible in the bi-monthly data of 1938, i.e, that a submarine ridge ("Santa Rosa—Cortes Ridge") extended about 100 miles southeastward from Santa Rosa Island in such a way as to indicate (perhaps to partly constitute) a boundary between a shoreward slack-water province and a seaward stream-flow province. The importance of this discovery may be understood from the fact that in each of the six cruises for 1940 it was possible to characterize the two areas by notation of differences in the diatom populations occurring in them as related to stream flow and eddy systems. Although the line from San Luis Obispo was not used in 1940, the relation of stream-flow populations was such as to indicate that it would have shown abundances even larger in 1940 than they were in 1938, i.e., the water masses entering the observed area from the more northerly section (an area of strong upwelling) were already thickly populated in April cruises. To a large extent the distinction between the two provinces in April was both quantitative and qualitative, i.e., the seaward stream-flow province showed more stations with very heavy populations and its dominant species of diatoms was different. *Chaetoceros costatus* Pav. showed most abundance in it as contrasted with the dominance of *Chaetoceros radicans* Schütt. in the other.The list of genera and species of diatoms in the 1940 cruises resembled that for 1938. A striking biological phenomenon having unidentified relationships was the excessive abundance of the flagellate *Phaeocystis* in the slack-water province especially in late April and in May (most stations). Presumably it would compete with diatoms on account of its similarity in nutrition as well as on account of its occupation of space but definite information is not available. The 1940 report is being offered to the University of California Press for publication.

At the time of this writing, examination of data for the monthly cruises of 1941 has advanced far enough to show that the time intervals were too long to permit the kind of detail in analysis of data found possitble for 1940.

However, the frequency of observations was sufficient to reveal differences in the populations on the two sides of the Santa Rosa-Cortes Ridge although they were much less distinct than in April of 1940 and although their relationships to water movements were much more difficult to trace, mainly because stream flow was much less distinctly developed in 1941 and because the pressure systems of oceanic water and the eddy systems of the observed areas were both more numerous and more complicated than they were in 1940. Nearly the same lists of genera and species of diatoms were recorded for 1941 but *Chaetoceros costatus* Pav. lacked prominence, being replaced in part by *Ch. compressus* Laud. *Ch. radicans* Schütt. retained its slack-water ascendancy in abundances, apparently, although surpassed by *Nitzschia seriata* Cl. in frequency of occurrences. *Phaeocystis* was not observed in 1941.

For the three years 1938, 1940, and 1941 the total number of catches of marine plankton diatoms was 5,394, nearly 800 at each of seven levels taken at stations ranging from relatively shallow locations near shore to those over oceanic depths. Abundances at particular levels tended to be much alike from 20 m to 50m, a little less at 10m and the surface and much less at 60m. So far as Southern California is concerned the "photic zone" is definitely above 60m. So far as noticed this condition of vertical zonation holds true near shore as well as off shore and is dependent on circulation of water masses rather than on their geographic or topographic relationships, as such. It is probable also that horizontal zonation, especially the distinctiveness of the stream-flow province and the slack-water province, is dependent primarily on circulation, especially oceanic and atmospheric circulations responsible for the strength of development of upwelling and for the rates and extents of flow of the California Current and of the Coastal Counter-current.

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Occurrence of the Bramble Shark in California

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OCCURRENCE OF THE BRAMBLE SHARK *(ECHINORHINUS BRUCUS)* IN CALIFORNIA[1]

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On the basis of a photograph of a 62-inch, 100-pound specimen caught off Santa Barbara, California, in July, 1939, it has been suspected by California ichthyologists that the very rare but wide-ranging bramble shark, *Echinorhinus brucus* (Bonnaterre), occurs along the California coast. Since the shark was not preserved and the head had obviously been mutilated by an injury that had healed, and since this species had never been reported from near California, the identification did not seem assured and the record has not been published. This strange shark was examined and photographed at the shark processing plant at Moss Landing, California, by a fish and game warden, Charles Holtzhauser, who gave the notes and picture to Robert D. Byers, then on the research staff of the Bureau of Marine Fisheries. The data were then referred to Dr. George S. Myers of Stanford University, who made the identification on the basis of the photograph.

FIG. 16. Bramble shark six feet five inches long, caught off Los Angeles County in 1944: the first record for the eastern Pacific. Photograph taken by Donald H. Fry, Jr., from fresh specimen on day of capture.

The occurrence of the bramble shark in California is now definitely confirmed. On August 21, 1944, Capt. John DiMeglio of the boat "Arcturus" took a specimen more than six feet long near Point Vicente in Los Angeles County. It was caught in a gill-net that was set in 50 to 55 fathoms off Portuguese Bend (approximate position: Lat. 33° 43.0′ N., Long. 118° 22.5′ W.). Not recognizing the kind, Capt. DiMeglio pre-

[1] Contributions from the Scripps Institution of Oceanography New Series, No. 250. Submitted for publication, December, 1944.

sented the strange shark, eviscerated, to the California State Fisheries Laboratory. It has been donated to the United States National Museum, where it has been given catalogue number 130667. This is apparently the only specimen of the genus that is preserved in any North American museum.

So far as we can find, no record of this kind of shark from the eastern Pacific has been published. The only North American record appears to remain that of a seven-foot specimen which was washed ashore at Provincetown, Massachusetts, in December, 1878 (Goode and Bean, 1879, p. 31). The second and probably the only other report for the New World is that of an example about two and one-half meters (nearly ten feet) long from Mar del Plata, in the Province of Buenos Aires, Argentina (Berg, 1898, p. 10).

The bramble shark has been reported as somewhat common only on the Atlantic coast of Europe. It has also been recorded from the Mediterranean Sea and from West and South Africa, Australia, Tasmania, New Zealand and Japan (detailed references will be cited by Bigelow and Schroeder in their forthcoming treatise on the elasmobranch fishes of the western North Atlantic). It probably has a wide range in temperate and subtropical waters.

An Hawaiian specimen described by Pietschmann (1928, p. 297; 1930, pp. 3-4, Pl. 1 and Fig. 1) as *Echinorhinus cookei* seems to fall within the range of variation assigned to *E. brucus*. Pending a thorough comparative study of the genus, we regard this nominal species, and also *E. obesus* Smith from South Africa and *E. (Rubusqualus) mcCoyi* Whitley of Australia, as synonyms of *E. brucus*. Dr. Bigelow has compared the photographs of our specimen with sketches of a European specimen just made by Col. Tenison at the British Museum, and writes that this comparison confirms the view that there is no difference between the Pacific and Atlantic forms of *Echinorhinus*. We follow Garman (1913, p. 243) and more recent authors in adopting the name *E. brucus* (Bonnaterre, 1788) in preference to that of *E. spinosus* (Gmelin, 1789), on the basis of priority. We have, however, made no special study of the dates of publication in question. The synonymy of *E. brucus* will be treated in the monograph by Bigelow and Schroeder referred to above.

An outstanding character of this species of shark is the lack of an anal fin coupled with the small size of the two dorsal fins, of which the anterior one originates about opposite the insertion of the long-based pelvic. The peculiar teeth, similar in each jaw, have a very oblique main cusp and, at each side, a single subhorizontal secondary cusp (published descriptions and figures indicate that two or even three secondary cusps may be developed on one or both sides). The teeth number 12+13=25 in the upper jaw and 12+11=23 in the lower (left side counted first), and thus fall within the range of 22 to 26 in each jaw, as commonly accredited to the species. The skin is distinctively armed with isolated tubercular scales, each with a hard stellate base and a small spine at the summit (hence the common name "bramble shark"). The nostrils are divided by a sharply pointed flap from the front margin. There is a short fold around the corner of the mouth. Most of these specific characters are well shown in the two photographs of the California specimen (figures 16 and 17). After two months in cold storage this specimen

was almost uniform dark brown, without clear indications of the dark spots reported in some descriptions.

Measurements follow of the California specimen, taken on the left side with the aid of special tuna-measuring calipers on the fresh specimen as soon as it had largely thawed out after having been hard-frozen for two months. The proportions are expressed as thousandths of the total length (196 centimeters). Greatest depth of body, about 141. Least depth of caudal peduncle, 62. Distance from tip of snout to first gill-slit, 192; to last gill-slit, 261; to insertion of pectoral fin, 260; to insertion of pelvic, 583; to origin of first dorsal fin, 590. Distance between origins of dorsal fins, 103. Interdorsal space, 39. Distance between bases of second dorsal and caudal fins, 37. Length of front

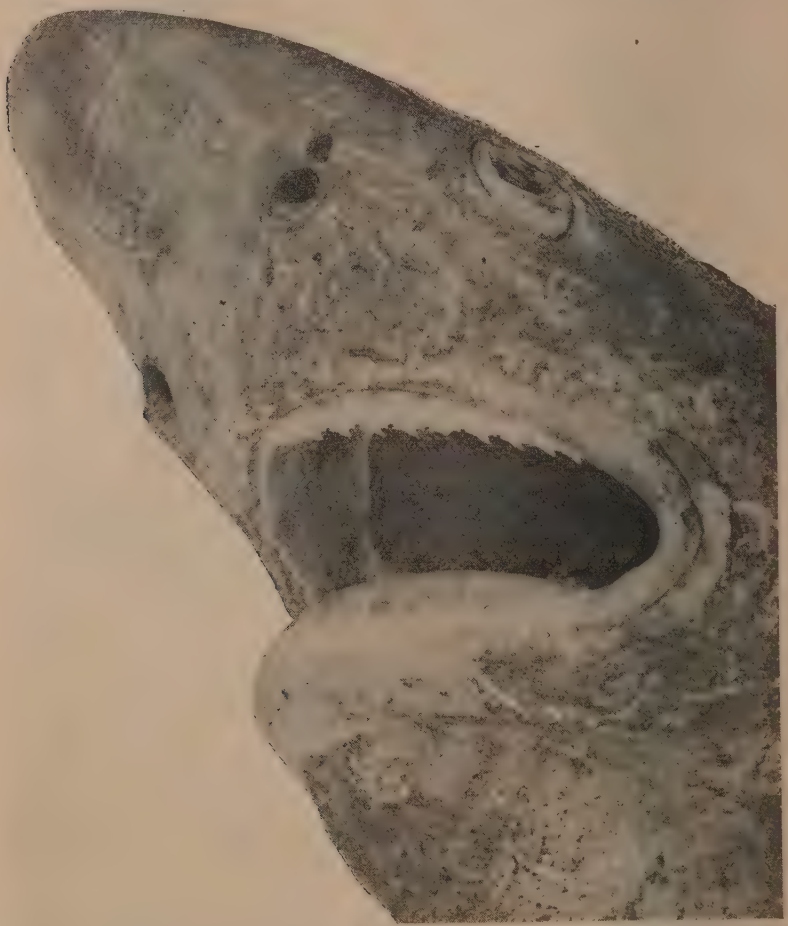

FIG. 17. Head of the California specimen of *Echinorhinus brucus*, showing structure of mouth, lips, teeth and nostrils, and the arrangement of the prickly scales. Photograph by Donald H. Fry, Jr.

margins of fins: first dorsal, 97; second dorsal, 88; upper caudal lobe, 218; lower caudal lobe, 117; pectoral, 115; pelvic, 89. Length of base of fins: first dorsal, 55; second dorsal, 51; pectoral, 72; pelvic, 104. Distance from origin of first dorsal fin to lateral line, 51. Height of first gill-slit, 44; of last gill-slit, 65. Length of snout: preocular, 81; preoral (from fold of lip), 72. Least distance between nostrils, 45. Width of left nostril, 15. Least interorbital width, 91. Length of orbit, 18. Suborbital width, 24. Width of mouth overall, 111. Length of mouth perpendicular to line joining ends of jaws, 41. Length of grooves at corner of mouth: upper, 16; lower, 19. Depth of snout above front of mouth, 51.

Although it was six feet, five inches long prior to preservation the male specimen at hand does not appear to have attained full maturity, for its claspers are very simple in structure, with merely a groove along one side, and are short, not reaching the posterior angle of the pelvic fin.

The taking of the bramble shark in California is a prompt confirmation of the opinion recently expressed in this journal by Barnhart and Hubbs (1944, p. 53) to the effect that many discoveries will follow upon a more thorough exploration of the fish fauna of the moderate depths along the coast of this State. Probably *Echinorhinus* will prove to be much less rare in California than the available data would seem to indicate.

Acknowledgements

For information and references dealing with the distribution of this shark we are particularly indebted to Henry B. Bigelow of the Museum of Comparative Zoology of Harvard University. Further advice has been received from Leonard P. Schultz of the United States Natural Museum and from three California ichthyologists, George S. Myers and Rolf L. Bolin of Stanford University and W. I. Follett of Oakland. Robert D. Byers, now of the Fish and Wildlife Service, has given data on the specimen that was caught off Santa Barbara. We also thank the Union Ice and Storage Company for the cold storage of the specimen. Donald H. Fry, Jr., of the California Division of Fish and Game, cooperated by taking the two photographs here reproduced.

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Contribution No. 251

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LITHOLOGY OF THE SEA FLOOR OFF SOUTHERN CALIFORNIA

BY K. O. EMERY AND F. P. SHEPARD

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ABSTRACT

Rocks obtained from the sea floor off the southern California coast principally during the 1938 cruises of the E. W. Scripps have been studied in the laboratory, and their petrographic character and fossil content determined. Rock was obtained from 132 localities in such environments as the narrow continental shelf, escarpments, hills, and the walls of submarine canyons.

Large size, angularity, quantity of fragments in a single haul, and the presence of fresh fractures suggest that many of the samples are representative of the bedrock outcropping at the sampling locality. The material recovered includes sedimentary, igneous, and metamorphic types. Ages were determined partly by fossil content and partly by lithological comparison with rocks outcropping on the adjacent land. Triassic-Jurassic, Cretaceous, Eocene, Miocene, and Pliocene are all represented, with Miocene rocks by far the most common. The igneous rocks are predominantly andesite, although some basalt was found. The chief conclusion from this reconnaissance work is that, aside from the abundance of phosphorite, the submerged basin and range province off the southern California coast is remarkably similar lithologically to that of the bordering land areas.

INTRODUCTION

While rocks of much of the earth's land area have been studied and mapped, s oceanic rocks are practically unknown because of the difficulty of procuring samp Most of the available information is very general and is based on collections made oceanographic expeditions (Murray and Renard, 1891). Actual maping of outcr on the sea floor has been restricted to small areas such as the English Channel, wh a comprehensive study was made by Dangeard (1928).

In 1938 a program of geological investigation of the sea floor bordering Califor was carried on in the schooner E. W. Scripps under the direction of Shepard. Abo 100 dredgings for rock were made off the southern California coast. These ro samples and other collections from the same area have been studied to obtain rough picture of the geology of this submerged area. Additional lithologic da were derived from the islands and the adjacent mainland.

Although an insufficient number of samples has been collected to permit the co struction of a geological map, enough material is available to give a very gene idea of the distribution of the rock formations on the ocean floor off southern Ca fornia. Interpretations have been facilitated by contour maps (Shepard a Emery, 1941, Charts I, II) based on several hundred thousand soundings made the U. S. Coast and Geodetic Survey.

ACKNOWLEDGMENTS

The collection of the samples was made possible through a grant from the Penro Bequest of The Geological Society of America and through the co-operation of t Scripps Institution of Oceanography, which loaned the vessel E. W. Scripps.

In 1938 94 rock samples were collected with dredges, snappers, and coring devic Twenty-eight samples were collected by Dr. Roger Revelle in 1936 and 1939 and Shepard in 1935 using the Scripps and the E. W. Scripps. Nine rock samples fro the area were collected with a snapper by Commander O. W. Swainson of the Coa and Geodetic Survey vessel Pioneer. One additional core sample was obtained F. M. Varney and L. R. Redwine.

The University of Illinois co-operated by giving two fellowships *in absentia* Emery and leaves of absence to Shepard. Especial gratitude is due Dr. R. Dietz who made many of the preliminary rock descriptions and assisted in th marine work; to Mr. M. L. Natland, who kindly identified the Foraminifera many of the sedimentary rocks; to Dr. P. D. Krynine, who made a careful analys of the manuscript; and to Dr. Roger Revelle, who assisted in the collection of th rocks and made many suggestions regarding their study. Appreciation is also e pressed to Dr. S. G. Wissler and Dr. K. E. Lohman, who made other faunal determ nations, and to Dr. A. O. Woodford who helped check identifications of metamorph rocks. Assistance in the preparation of these materials was furnished by personn of the Works Progress Administration (Official Projects 465-03-3-403 and 665-0 3-141) and the National Youth Administration.

DESCRIPTION OF AREA

As described elsewhere (Shepard and Emery, 1941, p. 2–29) the sea floor off southern California consists of a series of banks and basins between the narrow continental shelf and the steep continental slope. This area has been given the name "continental borderland." Many of the slopes bordering the banks are straight and steep and in places descend with unchanged gradient into the deepest part of an adjoining basin. They are therefore thought to be fault scarps. Structural trends shown by these supposed fault scarps are not uniform throughout the borderland but in general they parallel structural trends of the adjacent mainland or islands. The basins on the sea floor also have their counterpart on land in such basins as those of Ventura, Los Angeles, San Fernando, San Gabriel, and San Bernadino.

Eleven major basins are present and as shown by Revelle and Shepard (1939, p. 273, 274) they are the chief sites of deposition of the fine-grained debris carried out from the land. The near-shore basins have the flattest and broadest bottoms (Pl. 1) presumably indicating a greater filling by sediments. Several hundred sediment samples taken from the E. W. Scripps and many hundred others noted on Coast and Geodetic Survey charts indicate the characteristic presence of mud and a small amount of sand in the basins. Basins constitute about 21 per cent of the borderland area, and other flat-bottomed muddy areas, such as the San Diego Trough, make up an additional 9 per cent. From this area of about one third the borderland, it has been impractical to obtain lithologic data except from a few small hills which rise above the sediment.

Submarine mountains, many rising several thousand feet above their surroundings, separate the basins. Some of these mountains have deeply submerged summits. Others such as Cortes, Tanner, and Fortymile banks reach nearly to the surface, and still others rise above the surface as islands. Many of the submarine mountains have flat tops which, like the terraces on the islands and mainland, may be due to wave planation during the past. Charts of the U. S. Coast and Geodetic Survey record the characteristic presence of sand, gravel, or rock on the banks in contrast to the mud of the basins (Revelle and Shepard, 1939, Fig. 1, p. 248). Since the banks and other elevations are usually separated by basins, each is an individual unit for lithologic study, although some correlations can be made from one to another.

SAMPLES

All large rock samples were recovered by large bucket dredges having a wire netting bottom. One type is cylindrical (Shepard and Emery, 1941, Pl. 5, fig. 2), 30 inches long, and has a diameter of 18 inches. A rectangular type 36 by 36 by 12 inches (Shepard, 1941, Pl. 2, fig. 1) was also used successfully. Small samples were obtained by a dredge made of a short length of 4-inch pipe. A few other small rock samples were obtained with a snapper (Hough, 1939, Fig. 15). Small rock chips or pebbles were also found in some sediment samples taken by a large gravity corer (Emery and Dietz, 1941, Pl. 1).

The material obtained in the samples may be representative of the rocks ou cropping at or near the locality, or it may have been transported from a distant ou crop to the site of sampling. Various criteria distinguish which alternative is mo likely for a given sample (Dangeard, 1928, p. 44–53). While no single criterion infallible, substantial evidence is obtained by the concurrence of several. Featur which suggest sampling at or near rock outcrops are as follows:

(1) Fresh fractures
(2) Large size of individual rocks
(3) Abundant rocks of similar lithology
(4) General angularity
(5) Fragile or poorly consolidated rock
(6) Catching of the dredge on rock firm enough to stop the ship's progress abruptly
(7) Strong pull on the accumulator spring of the dredging boom.

Features of rock samples which suggest transport include:

(1) Varied lithology
(2) General rounded character
(3) Small size of individual rocks.

The widespread and deep beveled bank tops and the submarine canyons of th area indicate that waves, currents, and probably streams were important transpor ing agencies in the area during the past. Mudflows (Shepard and Emery, 194 p. 94–103) and landslides on the sea floor may also be important.

If, as seems likely, the banks and islands were already separated by basins whe they were partially beveled by wave action, neither beach nor stream transport woul have involved transport from one bank to another. Rafting by kelp (Emery an Tschudy, 1941), driftwood, and marine mammals (Emery, 1941) would have pr vided only a small amount of transportation from distant areas. Accordingl abundant rock of uniform lithology, even if obviously transported, may very like have been derived from the same bank as that from which it was dredged (Twe hofel, 1936). Conclusions as to the nature of rock outcropping on a bank may ther fore be based to some extent on samples containing transported pebbles, althoug samples consisting of freshly broken ledge rock provide a more certain basis. Fu thermore, phosphorite containing numerous Miocene Foraminifera indicate the pre ence of Miocene rocks at no great distance, even though the phosphorite may be more recent age (Dietz, Emery, and Shepard, 1942).

AGE AND DISTRIBUTION OF ROCK TYPES

GENERAL

The 5558 individual specimens have been separated into 27 major lithologic type Classification was made chiefly by microscopic examination of freshly broken su faces and polished sections. Approximately 3000 polished sections were mad When necessary, chips were crushed and studied by oil-immersion methods. Abo 200 thin sections were prepared. Age determination was made largely on the bas of foraminiferal content by M. L. Natland. Diatoms and megafossils also prov

value. Age determinations of many of the rocks were also made by lithologic mparison with characteristic types of known age outcropping on shore. The tter method is obviously less satisfactory than identification through fossil content d was therefore restricted to more unique rocks. Chief of these are some of the iocene cherts and limestones, and Franciscan metamorphics.

Data on rocks outcropping on the islands were obtained from field work by the thors and published reports as follows: Los Coronados (Woodford, 1925); San emente (Smith, 1897b); Catalina (Smith, 1897a); Santa Barbara (Kemnitzer, un-blished manuscript; Kleinpell, 1938, p. 164); San Nicolas (Kemnitzer, 1936, and published manuscript); Anacapa (Yates, 1890); Santa Cruz (Bremner, 1932); nta Rosa (Kew, 1927; Bremner, 1933); and San Miguel (Bremner, 1933).

A rough picture of the lithology of the borderland is given by the frequency of currence of each rock type as shown in Table 1. Percentage frequency of the total mber of rock fragments (5558) exaggerates the importance of rocks such as phos-orite, barite concretions, and sandstone which were found as very numerous small agments in several dredgings. At 105 stations, rock was taken at or near outcrops. he percentage of the 105 stations at which a given type of rock was found depends the ease with which that rock can be broken from the outcrop by sampling devices. s a result, such rocks as mudstone and shale appear inordinately abundant com-red to the volcanic rocks. Furthermore, because of the small number of stations outcrops, the abundance of such rare rocks as barite concretions found only at one ation is exaggerated. Percentage of the total number of stations (132) at which y quantity of a given type of rock was found may be more representative, but, cause more than one type was found at most stations, the total of these percentages more than 100 per cent. After reduction to 100 per cent, these percentage fre-encies (Last column, Table 1) appear to be the best obtainable figures for the rela-ve abundance of the various types of rocks, but they, like all the other methods of pressing relative abundance, depend on the geographical distribution of the ations.

SEDIMENTARY ROCKS

Sedimentary types constitute 80 per cent of all the pieces of rock obtained from e shelf bordering the mainland and 67 per cent of all those from the off-shore area yond the shelf. In age the sedimentary rocks vary from Jurassic (?) to Quaternary able 2). The age at many stations was determined by fossil content or by litho-gic similarity to rocks of known age on land.

The oldest, found west of San Nicolas Island along the top of the continental pe (Stations 121, *122*, 124, *125*[1]), are unfossiliferous sandstones and chert similar Franciscan (Jurassic?) rocks of the mainland.

Cretaceous rocks were identified only in the submarine canyon off La Jolla (Pl. 1, ations *11*, *12*, 13, 14). The lack of other submarine outcrops of Cretaceous rock in line with the absence of rocks of this age on the islands and on the coastal por-

[1] Italicized station numbers are those where rock is believed to have been taken from outcrops. More complete a are given in the appendix.

TABLE 1.—*Percentage frequency of rocks*

	Pieces		Stations from which evidence of outcrops was obtained		All Stations		
	Number	Percentage of total	Number	Percentage	Number	Percentage of total (132)	Lithology Frequency (Previous column reduced to 100%)
Sedimentary Rocks (total)	*4052*	*72.9*	*91*	*86.7*	*188*		*60.2*
Phosphorite	1333	24.0	17	16.2	43	32.5	13.8
Limestone	487	8.8	19	18.2	38	28.7	12.2
Sandstone	662	11.9	14	13.3	30	22.7	9.6
Mudstone	401	7.2	16	15.3	21	15.9	6.7
Shale	257	4.6	12	11.4	19	14.4	6.1
Conglomerate	192	3.5	4	3.8	14	10.6	4.5
Chert	190	3.4	5	4.8	12	9.1	3.9
Tuff	56	1.0	1	1.0	4	3.0	1.3
Breccia	202	3.6	1	1.0	2	1.5	0.6
Opal	10	0.2	0	0.0	2	1.5	0.6
Barite concretions	250	4.5	1	0.9	1	0.8	0.3
Manganese oxide	11	0.2	1	0.9	1	0.8	0.3
Spiculite	1	0.0	0	0.0	1	0.8	0.3
Igneous Rocks (total)	*1261*	*22.7*	*10*	*9.5*	*99*		*31.8*
Andesite	761	13.7	4	3.8	34	25.7	10.9
Basalt	234	4.2	5	4.8	23	17.4	7.4
Granite	132	2.4	0	0.0	14	10.6	4.5
Rhyolite	23	0.4	0	0.0	8	6.1	2.6
Andesite-basalt	84	1.5	0	0.0	7	5.3	2.2
Quartz	10	0.2	0	0.0	4	3.0	1.3
Dacite	4	0.1	0	0.0	4	3.0	1.3
Breccia	11	0.2	1	0.9	3	2.3	1.0
Granodiorite	2	0.0	0	0.0	2	1.5	0.6
Metamorphic Rocks (total)	*245*	*4.4*	*4*	*3.8*	*25*		*8.0*
Schist	212	3.8	3	2.9	12	9.1	3.8
Quartzite	18	0.3	1	0.9	5	3.8	1.6
Metavolcanics	9	0.2	0	0.0	3	2.3	1.0
Slate	4	0.1	0	0.0	3	2.3	1.0
Metasediments	2	0.0	0	0.0	2	1.5	0.6
Total of all types	*5558*	*100.0*	*105*	*100.0*	*312*		*100.0*

tion of the mainland except at La Jolla and northwest of Santa Monica Bay. (J
kins, 1938).

Eocene rocks were found on the shelf south of La Jolla (Stations 6, 7, *8*, *9*), in
Jolla Canyon, particularly the northeast fork (Stations 10, 13, *14*, *15*, *16*), and
the shelf just north of San Nicolas Island (Station *112*). In these areas Eocene r
is abundant on the adjacent land (Hanna, 1926, p. 215; Kemnitzer, 1936). Sa
Cruz, Santa Rosa, and San Miguel islands also consist in part of Eocene strata.

On the mainland, Miocene sedimentary rocks are widespread along the coast from Oceanside to beyond Point Conception at the northwest edge of the borderland (Jenkins, 1938) and are also reported from all the islands except San Nicolas. Although not occurring on the mainland south of Oceanside (Hertlein and Grant, 1944, p. 45, 46), marine sedimentary rocks of Miocene or probable Miocene age are present on Los Coronados Islands, in Coronado Canyon (Stations 1, 2, *3*), and in outer La Jolla Canyon (Station *19*). Farther north, Miocene rocks are very abundant on the sea floor, identified either through faunal content or lithology in about two thirds of the rock samples from the shelf and canyons between San Pedro Seavalley and Huneme Canyon (Stations *22*, *24A*, *27*, 29, *30*, *31*, *32*, 33, *34*, *35*, 36, *38*, *39*?, *43*, 44, *45*?, 46, 49). The close resemblance to those outcropping on the Palos Verdes Hills (Woodring, Bramlette, and Kleinpell, 1936) and the Santa Monica Mountains (Hoots, 1931) clearly shows a seaward continuation of the formations found on land. Phosphorite is an exception since it is much more abundant on the sea floor than on land; however, this material may be of Quaternary age though it contains reworked Miocene fossils (Dietz, Emery, and Shepard, 1942).

A similar abundance of Miocene sedimentary rocks is found offshore just southwest of San Clemente Island, where practically every sample from the walls of the "Rift Valley" (Stations *71*, *72*, *73*, *74*, *76*), and from the northwest slope of Fortymile Bank (Stations 67, *69*, *70*), contains probable Miocene rock. Miocene sediments are also present on parts of Thirtymile Bank (Stations 56, *58*) and as transported fragments on Fortymile Bank (Stations 62, 65, 66). The paucity of Miocene sediments on San Clemente Island, where the rocks are dominantly Miocene volcanics, contrasts with their abundance on the sea floor to the southeast. Several small rock samples from the vicinity of Tanner and Cortes banks also contain sedimentary rocks of Miocene age (Stations 100, 101, *106*, 107, 108, 110), indicating that these banks are in part underlain by Miocene sediments. Similarly, Miocene rocks were obtained from the broad plateau at the edge of the borderland west of San Nicolas Island (Stations 121, 122, *123*, 124, 126).

Rocks of Miocene age have been identified at 42 stations or 32 per cent of all the sea-floor stations. Ten additional stations (7 per cent of total) had phosphorite containing Miocene fossils or of that type (Table 3). At 23 stations Miocene rock other than phosphorite was adjudged to have been taken at or near outcrops. The fossils show that practically all the material is of Middle or Late Miocene age. The rocks in decreasing order of number of stations are limestone, mudstone, chert, shale, conglomerate and sandstone (Table 2). Phosphorite, because of its special problems, was omitted from Table 2 though it indicates the proximity of Miocene rocks where it contains Miocene Foraminifera. Krynine (personal communication) pointed out that this order of abundance contrasts with the Miocene as known on land where shale and sandstone are much more abundant than limestone. The processes which led to formation of rounded cobbles on the sea floor probably concentrated the more resistant rocks like limestone and chert so that they appear more frequent than the less resistant shales and sandstones.

There appears to be a scarcity of Pliocene rocks in both the submerged and exposed portions of the borderland. Submarine sampling produced Pliocene material other

TABLE 2.—*Summary of data on the distribution of sedimentary rocks*
(Excluding phosphorites)

Age	Conglomerate	Sandstone	Shale	Mudstone	Limestone	Chert
Jurassic(?)-Franciscan		(2) *122*, *125*				(3) 121, 124, 125
Cretaceous			(4) *11*, **12**, 13, 14			
Eocene	(10) 6, 7, *8*, 10, 13, *14*, *15*, *16*, 20?, 21?	(3) *9*, *18*?, *112*	(3) **9**, *17*?, *18*?		(1) *112*	
Miocene	(3) 1, 3, 19?	(3) 1, 2, *3*	(8) *3*, 33, **34**, 36, *43*, 46, 49, 65	(13) **19**, **24A**, **30**, **31**, *32*, **38**, **69**, **71**, **74**, **76**, **101**, **106**, **110**	(19) *22*, *27*, 29, *32*, 33, *35*, *39*?, *45*?, **69**, *70*, **72**, *74*, *76*, 94?, 107, 121, 122, *123*, 126	(9) *32*, 33, 44, *58*, 66, **73**, **74**, **76**, **82**
Pliocene and Quaternary	(1) **35**			(5) **24**, **84**, **87**, **89**, **107**		
Indeterminate age		(22) 4, *8*, 19, *23*, *41*, *42*, 46, 56, 65, 66, *69*, *74*, *76*, 82, *89*, 94, 107, 108, 111, 118, 121, 123	(4) *15*, *73*, *76*, 82	(3) *25*, 68, 82	(18) 1, 2, 6, *23*, 24, 26, *31*, *34*, *58*, 65, 66, *71*, 93, 106, 111, *116*, 124, 125	

(1) Figures in parentheses indicate total number of stations.
(2) Other figures give the reference number of locality.
(3) Figures in italics show that the specimen came from an outcrop locality.
(4) Figures in boldface type indicate that the age identification is based on paleontological evidence.

an phosphorite only in San Pedro Seavalley (Station *24*), in Santa Monica Canyon Station 35), in two samples off the northeast side of San Clemente Island (Stations *4*, *87*), and in one sample from the sill at the south end of San Nicolas Basin (Station

TABLE 3.—*Phosphorite*

Containing Miocene fossils			Containing Pliocene or Quaternary fossils			Type similar to that containing Miocene fossils			Indeterminate age		
Station number	Number of pieces	Maximum diameter (cm.)	Station number	Number of pieces	Maximum diameter (cm.)	Station number	Number of pieces	Maximum diameter (cm.)	Station number	Number of pieces	Maximum diameter (cm.)
*32**	50	15	55	1	1 (in andesite cobble)	19	1	3	5	6	0.7
35	28	52				*27*	86	16	38	1	2
56	1	5				29	1	3	61	1	0.6
58	?	(nodules in cgl.)	*58*	6	25 (matrix)	33	2	2	75	3	1
62	?	(nodules in cgl.)	*62*	2	32 (matrix)	*60*	35	2	77	1	2
65	6	3	*126*	6	60 (matrix)	68	2	1.5	80	1	2
67	100	22				*74*	1	8	*89*	20	1
69	300	30				107	10	4	97	1	0.2
70	461	15				109	5	3	98	1	2
71	6	30				110	3	2	*106*	10	2
100	2	1				119	2	4	113	2	4
108	7	1.5				125	4	4	117	1	?
121	100	18							127	6	0.3
122	2	4									
123	9	35									
124	40	30									
126	?	(nodules in cgl.)									
otal.....17			4			12			13		
erage number of pieces.....74				4			13			4	
erage maximum diameter—cm..... 18.9					30			4.4			1.4

* Italics refer to outcrop localities.

). From the elevation which forms the southeast end of the ridge through Tanner ank a fragment of mudstone (Station 107) contains Foraminifera ranging in age om lower Miocene to Pliocene.

At three stations Pliocene Foraminifera were found in a phosphorite matrix enclosg nodules containing Miocene Foraminifera. At one additional station phosphorite ving Pliocene Foraminifera occurred in a pholad boring in an andesite cobble. ecause of the poor consolidation of Pliocene mudstones this material in some other mples may have been mistaken for Quaternary muds. Therefore, when the Fora-

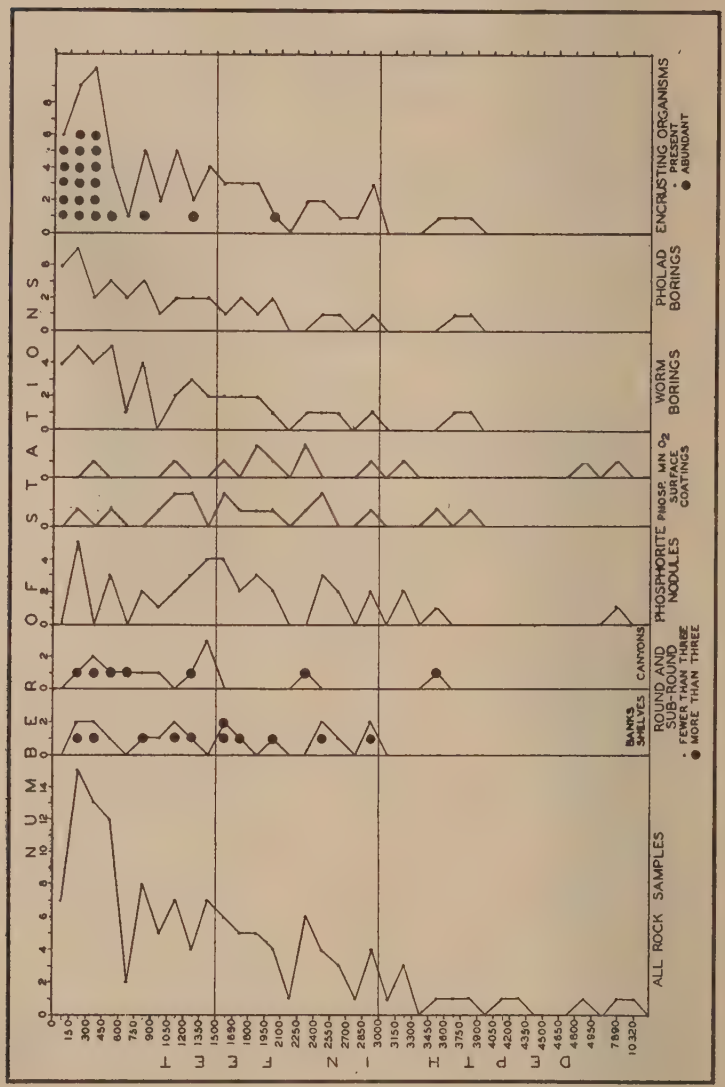

FIGURE 1.—*Rock-sample characteristics related to depth*

inifera in sediment samples from the area have been more completely investigated e number of submarine Pliocene outcrops may be increased.

Unconsolidated Quaternary sediments are, of course, widely distributed, mostly as lings in the basin and trough areas. Great thicknesses of such sediments exist in sins on land (Reed, 1933, p. 240). On submarine topographic highs Quaternary position may be represented only by the widespread phosphorite and foraminiferal nds.

Phosphorite presents a rather difficult problem in a study of lithology. At 17 ations (Table 3) phosphorite containing Miocene Foraminifera was found in samples nsisting of an average of 74 fragments having an average maximum diameter for ch station of nearly 20 cm. At 12 other stations containing an average of 13 frag- ents having an average maximum diameter of only 4 cm. no Foraminifera could be entified, but these samples showed lithologic affinities with those containing Miocene raminifera and are therefore probably of similar origin. At 13 other stations both e number and size of fragments was too small for lithologic comparison. At 3 sta- ons large blocks of phosphorite contained nodules lithologically and faunally like e more common phosphorite cemented into conglomerates by a matrix of a light- own open-textured phosphorite. This matrix contains Pliocene or Quaternary raminifera and is therefore unquestionably of Pliocene or Quaternary age. The osphorite containing Miocene Foraminifera may be of Miocene age, in which case is enormously more abundant on the present sea floor than on land at Miocene tcrops. This fact, with others, led Dietz, Emery, and Shepard (1942, p. 839–844) consider that it was more likely of Pliocene or Quaternary age but contained abun- nt reworked Miocene Foraminifera. If the latter were true, the content of Mio- ne Foraminifera at least indicates the proximity of Miocene rocks, and it is therefore nificant in estimating the location and abundance of Miocene rocks.

IGNEOUS ROCKS

Igneous rocks constitute 22.7 per cent of all the rock fragments or 9.5 per cent of the tcrops, or 31.8 per cent relative frequency (Table 1). No outcrops of granitic rocks re found. However, granite cobbles in a number of samples from Santa Monica y, particularly at the head of Santa Monica Canyon (Stations 33, 35), and a few unded granite pebbles in samples from San Pedro Seavalley (Station 26), Redondo nyon (Station 28), Dume Canyon (Station 40), and Hueneme Canyon (Stations , 47, 48, 49) may have been derived from the granites or aplites of the near-by nta Monica and San Gabriel mountains (Hoots, 1931, p. 89, 90; Jenkins, 1938). her occurrences in the borderland of debris from granites are too rare to deserve ich attention. A few samples contain diorite or granodiorite (Stations 34, 49). In contrast to intrusives, volcanics are found in many rock samples (Table 1), par- ularly in those from the offshore area. Chief of these are andesite and basalt which re classified according to the method described by Johannsen (1931). Andesite the most common, but from the nearshore area it is known only on Los Coronados ands and in Coronado Canyon (Stations 1, 2). Farther offshore it is very abun- nt, being found on two hills in the bottom of San Diego Trough (Stations *92*, 93),

on another hill southwest of Coronados Islands (Station *53*), on Thirtymile Bank (Stations 54, 55, 56, 57, 58), Fortymile Bank (Stations 63, 64, 65, 66, 67), and on the slope northeast of San Clemente Island (Stations 78, 79, 80, 81, *82*, 83, 84, 85, 86). It is also present in samples from the slope northwest of Fortymile Bank (Stations 69, 70) and on the elevation southeast of Tanner Bank (Station 107). In addition, most of the islands of southern California contain outcrops of andesite, and San Clemente Island consists dominantly of this rock.

Basalt is less common. It crops out in Dume Canyon (Station *37*) and is found in small samples from Cortes Bank (Stations 101, 102, *103*, 104) and from the elevation southeast of Tanner Bank (Stations 108, 109) and Northeast Bank (Stations 117, 118). It is also found at the base and top of the continental slope east of San Juan Seamount (Stations 127, 128) and on San Juan Seamount (Stations *129*, *130*, *131*). On land basalt is also found in small outcrops at Point Dume, the Palos Verdes Hills, and other points along the coast.

Rhyolite and dacite were usually encountered only as rare fragments among large rock samples. The only area in which either was dominant is the small elevation between Catalina and San Clemente islands, where a single dredging (Station 91) consists only of rhyolite. Like andesite and basalt, rhyolite is found on most of the islands, but dacite is reported only from San Clemente.

Little can be stated regarding the limits of outcrop of volcanics except that andesite probably dominates in the eastern half of the borderland, while basalt is more common in the western half. San Juan Seamount, which consists of basalt, is probably a volcanic cone. Lack of olivine and laboradorite indicates that the rock of the seamount is not more basic than basalts from the borderland, but the small amount of material recovered was so highly weathered that identifications were indefinite.

The limitations in submarine geological work make it particularly difficult to determine the age of igneous rocks. Extrusives found on the islands, however, are reported to be of middle or upper Miocene age. Similar rocks on the adjacent mainland are of the same general age (Woodring, Bramlette, Kleinpell, 1936, p. 135; Soper, 1938, p. 165, 166). By analogy a probable Miocene age may be assigned to the volcanics of the sea floor.

METAMORPHIC ROCKS

On the basis of lithologic and mineralogic character many metamorphic rocks recovered from the borderland are assigned to one of the series of metamorphics found on land. Exposed Franciscan (Jurassic?) metamorphics in the borderland region occur on Catalina Island (Woodford, 1924). Santa Cruz Island also consists in part of metamorphic rock which is thought to be of Triassic-Jurassic age but not necessarily Franciscan (Bremner, 1932, p. 13). Along the mainland coast, Franciscan rocks are found in the Palos Verdes Hills (Woodford, 1924, p. 49–51), and farther inland other metamorphic rocks, largely slates, occur in the Santa Ana Mountains.

On the sea floor metamorphic rock was encountered in the vicinity of Sixtymile Bank (Stations *50*, 51). The material from this area contains some crossite and is therefore considered a Franciscan schist (Woodford, 1924). A near-by bank yielded

hist (Station *52*) which appears to be more like the Pelona series of the pre-Cambrian an to the Franciscan (A. O. Woodford, personal communication). Pebbles of arious types of metamorphics are thinly but widely distributed near Fortymile and hirtymile banks, being found in 11 rock samples (Stations *56*, 58, 59, 62, *63*, 65, 66, , 69, 70, 71). Some of the specimens, though small, resemble the Franciscan schists that crossite or glaucophane is present. Other small schist fragments were found bottom samples from near Catalina Island (Stations 95, 96, 97).

Cobbles of schists similar in their content of glaucophane and crossite to those of ie Franciscan (Jurassic?) were found in a dredging in Coronado Canyon (Station 1). hese are probably derived from the Miocene San Onofre formation, a probable phase which crops out on the near-by Los Coronados Islands (Woodford, 1925, p. 163, 32, 183, 200). Similar material was obtained in La Jolla Canyon (Station 19).

Meta-igneous pebbles similar to those of the Black Mountain (Triassic-Jurassic) eries were found in dredgings from the shelf off San Diego (Stations 6, 7, *8*), from La olla Canyon (Stations 10, 13, *14*, *15*, *16*), and from Carlsbad Canyon (Stations 20, 1). These rocks are well rounded, and some are cemented into a conglomerate. ll are probably from Eocene conglomerates which on the near-by land are composed ostly of similar meta-igneous cobbles.

PALEOGEOGRAPHY

Reed (1933) published a series of paleogeographic maps of southern California and ie adjacent sea floor. This set was reproduced with minor changes by Reed and ollister in 1936. The submarine portion of these maps was based almost entirely n rock outcrops on islands, because no sea-floor samples were available. Now, how- er, enough samples have been obtained to make possible a partial check of the aps.

According to Reed (1933, p. 28, 73) the major part of the borderland has a Francis- an basement, while "Anacapia" (a mass which includes Anacapa, Santa Cruz, anta Rosa, and San Miguel islands) is underlain by granite. Among the sea-floor mples, pebbles of Franciscan sediments and metamorphics were found over much the area, while granite pebbles were found in abundance only near "Anacapia." hus the new data support Reed's division of the borderland, even though few of the mples consist of rock obtained from outcrops.

During the Cretaceous, as indicated by Reed (1933, p. 116), much of the borderland as probably low land or shallow sea. Cretaceous rocks are reported from none of ie islands and were not found in dredgings except near the shore at La Jolla. Simi- rly Eocene rocks were recognized only near San Nicolas Island and near La Jolla here their occurrence represents no disagreement with Reed's maps (Reed, 1933, p. 43). No Oligocene rocks were identified in the samples, thus indicating that there ay have been no deposition in the borderland at this time (Reed, 1933, p. 139).

Likewise sparsely distributed are samples containing lower Miocene rocks. These ere only tentatively recognized by incomplete foraminiferal evidence at two stations 07, 126). Both stations lie near the southwestern boundary of the "San Pedro eninsula" (Loel and Corey, 1932, p. 50; Reed, 1933, p. 165).

On the basis of island outcrops Reed (1933, p. 185) indicated a Middle Miocen land area south of the Santa Cruz Island group. Corey (1936) also postulated a high land in this general vicinity. The presence of a land area, "Catalinia," somewha farther south was suggested by Woodford (1925, p. 237, 238) to account for the pres ence of the San Onofre breccia along the mainland coast. This breccia is said to b the result of mudslides from a highland. At present these areas are largely occupie by basins. Few rock samples were taken there, and these added little to the dat available from island outcrops. However, many sea-floor samples containing a identifiable fauna were obtained south of San Clemente Island and San Nicola Island, where they show that marine Middle Miocene is abundantly represented Therefore, during the Middle Miocene "Catalinia" was probably more restricte than is shown by Reed's map. Probable San Onofre breccia on Los Coronado Islands and Franciscan metamorphics on the banks directly offshore from thes islands may indicate the presence of another former land area perhaps separate fron "Catalinia."

Because of the wide distribution of upper Miocene rocks on the islands Reed (1933 p. 218) showed most of the borderland as occupied by seas. This conclusion wa supported by the dredging of many fossiliferous upper Miocene rocks within this area Other rocks having no identifiable fauna were assigned a Miocene age through litho logic resemblance to rocks on land. Although the part of the Miocene to which eac of these rocks belongs is uncertain, their abundance shows that at some time durin the period the sea covered most of the borderland.

Reed's (1933, p. 252) Pliocene—Early Pleistocene map indicates that a landmas was present over most of the borderland, but Reed and Hollister (1936, p. 45) sugges that marine deposits of this age may occur throughout the area. As indicated pre viously Pliocene sediments were recognized in only four of the sea-floor samples two stations on the northeast submarine slope of San Clemente Island, one statio southwest of the island, and one station in San Pedro Seavalley. All but the San Pedro Seavalley locality lie within the landmass shown by Reed, so that his boundarie should be somewhat modified. Furthermore, most of the offshore basins probabl contain Pliocene deposits buried beneath more recent sediments.

TIME OF CANYON CUTTING

The walls of many of the California submarine canyons consist of well-consolidate rock, which must have been deposited before the canyons were formed. Where th age of this rock can be determined, an age limit for the canyons is indicated. Walls o La Jolla Canyon are composed of Cretaceous, Eocene, and Miocene rocks. Othe canyons having walls composed in part of middle or upper Miocene sedimentary rock are Coronado, San Pedro, Redondo, Santa Monica, Dume, Mugu, Hueneme, an Tanner canyons. Poorly consolidated Repetto (Pliocene) mudstone was dredge from the wall of a branch of San Pedro Seavalley, so it seems likely that at least thi valley was formed in post-Pliocene time. Other lines of evidence from this and othe areas suggest that these world-wide features were formed during the Pleistocen (Shepard and Emery, 1941, p. 126–133).

TIMES OF DIASTROPHISM

On many of the banks and islands, bedded upper Miocene shale, chert, and lime-
ne have been found. These sediments are entirely different from those being
med in the present bank environments and presumably were formed in a broad
bayment or basin. Late Miocene or post-Miocene diastrophism must, therefore,
e broken up the borderland into blocks and basins. Suggestive of a post-
ocene—pre-Pliocene time of block initiation is the extreme scarcity of Pliocene
rine sediments either on the islands or on the sea floor. If the blocks were
iated in pre-Pliocene time, sediments of Pliocene age would have accumulated
gely in the basins where they would now lie deeply buried, just as in the Los Angeles
l Ventura basins where great thicknesses of Pliocene sediments are encountered in
lling for oil (Reed and Hollister, 1936, p. 113; Natland, 1933). The most likely
ce where these sediments might be re-exposed is at the basin margins where recur-
t faulting might bring them to the surface. The finding of Pliocene sediments at
o stations on the scarp northeast of San Clemente Island supports this suggestion.
omarine elevations are now kept largely free of sediments, and it is reasonable to
ume that the same would also have been true during the Pliocene. Therefore, the
eral absence of material of Pliocene age on the banks and islands may indicate
t these areas were already topographic highs during the Pliocene.

An indication of more recent diastrophism is derived from a study of the submarine
oes. The slopes bordering most of the mainland shelf and the slope northeast of
n Nicolas Island are incised by submarine canyons suggestive of a fluviatile origin.
the other hand, the slopes which particularly resemble fault scarps like those
theast of San Clemente Island, along Fortymile Bank, and in the western part of
borderland (the continental slope) are virtually uncut by submarine canyons,
gesting that these scarps were formed or modified after the time of canyon cutting.
he canyons are Pleistocene in age, as suggested elsewhere (Shepard and Emery,
1, p. 126–133), then these faults appear to be Pleistocene or Recent. Also the
wport-Inglewood "fault" (Reed and Hollister, 1936, p. 125–133) appears to form a
dward continuation of the scarp on the east side of the San Diego Basin and the
ng Beach earthquake with an epicenter off Newport (Wood, 1933) presumably was
sed by a recurrent movement along this fault. Many other recent earthquakes
e been located off the southern California coast (Richter, 1940).

Also indicative of relatively recent movements are the fresh-looking terraces ob-
ved on most of the islands and recorded by earlier workers (Lawson, 1893; Smith,
0).

The absence of any appreciable continental shelf along the northeast side of San
mente Island, southwest of the Palos Verdes Hills, and in some other sections of
mainland indicate that movements have been too recent locally to allow much
e truncation. On the other hand, the presence of a narrow shelf at a nearly
form depth along most of the mainland coast and surrounding most of the islands
icates that differential movements at these places have not been of general impor-
ce for a considerable period of time.

SAN CLEMENTE "RIFT" VALLEY

On physiographic grounds it appears that there may have been large horizont shifting along the San Clemente "Rift" Valley (Shepard and Emery, 1941, p. 21–33 Comparison of rock samples from this area provides a possible test.

Dredgings from the summit of Fortymile Bank consist mostly of volcanics, whi those from the north end of the bank are chiefly of Miocene sedimentary rocks. Th samples in the "Rift" Valley show that it is a continuation of the Miocene sedimer tary rock area which forms the north slope of Fortymile Bank. Samples from bot walls consist of similar rocks. Northwest of the valley along the scarp which borde San Clemente Island, Miocene sedimentary rocks are generally absent, and in the place occur volcanics like those of the adjacent island, which also is composed dom nantly of volcanics. Both the high areas—San Clemente Island and Fortymile Bar —consist dominantly of hard extrusives, while the low area between, in which the dee valley exists, consists of sedimentary rock. This distribution of rocks is not partic larly suggestive of horizontal movement along the scarps, but the lithologic data a not very complete and are not conclusive.

PRESENT MARINE UNCONFORMITIES

Because there is little or no clastic deposition at present on the tops of banl (Shepard, 1941) only sand composed of the tests of Foraminifera and other organisn and grains of authigenic glauconite and phosphorite can accumulate. Apparent deposition of these materials is very slow since bare rock surfaces or loose cobbl are exposed at many places.

Some subround to round cobbles lie at great depth (Appendix and Fig. 1). A sing rounded cobble in a dredging may have been rafted to the sampling locality, but whe three or more such cobbles are present in a single dredging far from shore rafting highly improbable.

That rounding processes are not active at present is indicated by the presence encrusting organisms on many cobbles or on other associated rocks. These organisn are particularly abundant on rocks from water shallower than about 450 feet (Fig. 1 Organic encrustations and thin coatings of manganese oxide and phosphorite (Fig. Pl. 2, fig. 4; Pl. 3, fig. 1) found on many cobbles would probably be removed b violent rolling. Many rocks instead of becoming rounded are being made progre sively more angular through the action of boring mollusks as noted by Barrows (1917 Most of the borings are bottle-shaped cavities which altogether make up a lar portion of the rock volume (Pl. 2, fig. 2). The borers' activity is not restricted to so rocks since their holes are also found in hard volcanics (Pl. 2, fig. 4). Although mo common in shallow depths, borings were found as deep as 3600 feet, but it is n known whether they were made at such depth or whether submergence has tak place subsequent to the boring activities. In many dredgings there are several roc of similar lithology, all containing borings. For at least these samples, transportati after the time of boring is unlikely.

Rounded cobbles were found in rock samples at considerable depth in submari canyons and on banks. Those from canyons may have originated through fluviat

cesses, and those on banks may be due to wave action when the continental derland or portions of it stood relatively higher. The deepest dredging off thern California containing cobbles was made in the San Clemente "Rift" Valley depth of 3600 feet (Pl. 3, fig. 3). The maximum depth of cobbles obtained from banks is 2880 feet, but rounded fragments were most numerous in samples from ths of less than 600 feet.

Rocks in many of the drags are somewhat weathered, another indication of an conformity. This is commonly shown by the presence of an outer oxidized layer ighter color than the fresh rock in the center and ranging up to about 1 centimeter thickness. Chemical weathering is also shown by the alteration of olivine to ser-tine and by the development of palagonite in the rocks from San Juan Seamount. ether the weathering took place only under earlier subaerial conditions or is con-uing subaqueously is unknown.

INFLUENCE OF MAN

Although man's influence on harbors and beaches is well recognized, his effect on offshore areas is not so fully appreciated. Rather striking is the large number of cles dropped from ships and found in sea-floor dredgings. A broken oarlock, tar kets, paint cans, a beer can, a possible kite tail, rubber tubing, broken glass, and a tch box were recovered in dredgings off southern California. Cinders from ships' boxes were found at only three stations but are reported as very abundant in dgings from deep water in the Atlantic steamer lanes (Peach, 1912). Although y the cinders are likely to remain undecomposed and be incorporated permanently he sediments, the finding of other more perishable articles also shows the extent of n's activity.

SUMMARY AND CONCLUSIONS

Examination of dredge and core samples of the sea floor off southern California has wn that rock is present at many places on the shelves, on submarine canyon walls, on submarine elevations but is absent in the basins and troughs. The age of ny of the sedimentary rock samples was determined by M. L. Natland and K. E. man through their content of Foraminifera and diatoms. General age identifica-ns were made by a lithologic comparison with rocks found in outcrops on land.

Miocene or probable Miocene sedimentary rocks were found very widely distributed the continental borderland, occurring in over one third the rock samples. Vol-ics found in many other samples may alxo be of Miocene age, judging by the ndance of Miocene volcanics on the off-shore islands. Rocks of other ages were found in a few localities. Schists were encountered in abundance only in the thern portion of the submarine region, but isolated fragments of Jurassic (?) amorphics were found at a number of other points. Abundant sandstone of bable Jurassic age was found near the western margin of the area. Cretaceous ks were identified only near La Jolla and San Nicolas Island, although they also crop on the Santa Cruz chain of islands. Oligocene rocks were not recognized. ewise, Pliocene sediments seem to be very sparingly present, being recognized

principally near San Clemente Island. In general, the distribution of the rocks o the sea floor conforms to the paleogeographic maps given by Reed (1933) and Ree and Hollister (1936), though changes are necessary for the Middle Miocene and th Pliocene maps.

The widespread distribution on the sea floor of rocks similar to those found on lan precludes the possibility that the continental borderland off southern California is wave-built terrace dislocated by faults. Rock is present on the banks and th shelves and also forms the walls of submarine canyons which cut the shelves. Th numerous rock samples from La Jolla Canyon and other canyons substantiate thi point. On the wall of one canyon partially consolidated Pliocene sediments wer found, indicating that at least this canyon was formed in post-Pliocene time.

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EXPLANATION OF PLATES 2 AND 3

PLATE 2.—ROCK DREDGINGS

Figure

1.—Station 12, a dredging from a depth of 210 feet in La Jolla Canyon, showing the large quantity of Chico (Cretaceous) shale broken from the canyon walls. The large piece, upper left, is 45 cm. long. In contrast is the small size of the shale pebble from Station 13 and the round metavolcanic pebble from Station 10. Note also the kelp holdfasts picked up on the near-by beach.

2.—Limestone from Station 23, at a depth of 720 feet in San Pedro Seavalley, showing numerous borings made by organisms. Largest fragment is about 13 cm. long.

3.—Concretionary limestone recovered at Station 39 from 1380 feet in Dume Canyon. The origin of the hollow tube 60 cm. long is unknown.

4.—Rounded cobble of andesite which was bored by pholads after rounding. Phosphorite containing upper Pliocene or Quaternary Foraminifera partially fills some of the borings. A thin phosphatic film also covers the surface of the cobble. (Station 55, 1020 feet, Thirtymile Bank)

FIGURE 1

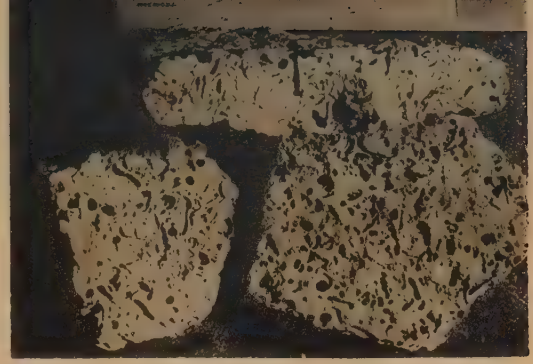

FIGURE 2

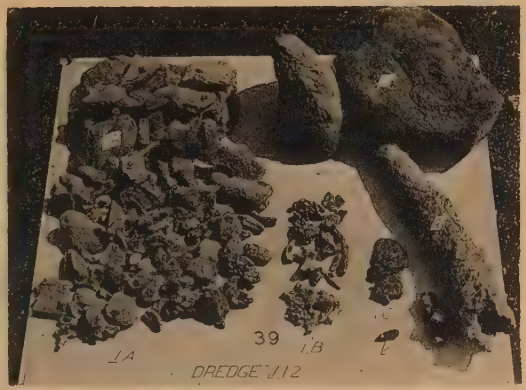

FIGURE 3

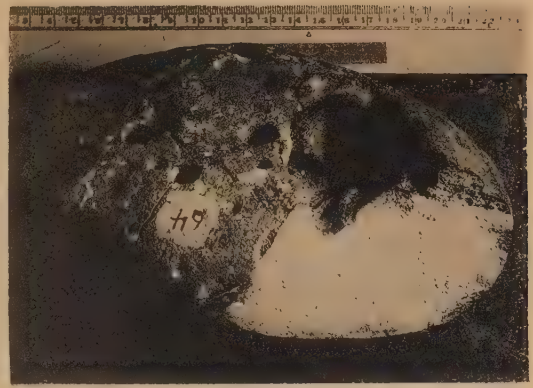

FIGURE 4

FIGURE 1

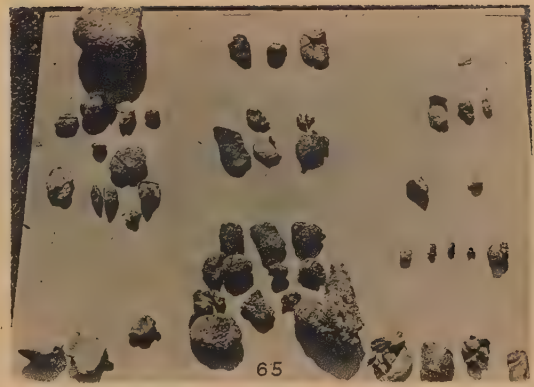

FIGURE 2

FIGURE 3

FIGURE 4

Plate 3.—ROCK DREDGINGS

gure
1.—Andesite block from Station 56, 1170 feet, Thirtymile Bank. Phosphorite forms a thin sur-ce covering. Note that encrusting organisms occur only on the top of the rock, indicating the un-ried portion.
2.—Partially rounded rocks from Station 65, 300 feet, Fortymile Bank. Note that many of the cks were broken in the laboratory. The large cobble of andesite, upper left, is 12 cm. in diameter.
3.—Material recovered at Station 71 from a depth of 3600 feet in the San Clemente "Rift" Valley. ote on the right the large pieces (45 cm. long) of fragile mudstone which could not have endured uch transportation. In contrast are several rounded cobbles of volcanics.
4.—Rocks dredged at Station 1 24 (1620 feet) and Station 126 (780 feet). Most of the material of ch dredging, including the largest blocks, consist of phosphorite. The large phosphorite block at e upper right is 60 cm. in diameter.

APPENDIX—INFORMATION CONCERNING SAMPLES

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
*1. Scr. 9377—Lat. 32°30.3′, Long. 117°20.0′; 396 feet; dredge; Coronado Canyon—south wall; transported**							
Andesite-besalt	14	6	SR	br.-bk.	porphyritic to trachytic		
Dacite	1	5	A	lt. gy.	finely crystalline		
Schist (cgl.)	3	2	A	gy.	albite-chlorite	Franciscan (Jur.?) prob. from Mio. cgl.	
Schist (cgl.)	1	2	A	lt. gn.	crossite-quartz	Franciscan (Jur.?) prob. from Mio. cgl.	
Quartzite	1	4	R	yel. gy.	coarse-grained		
Sandstone	8	6	A-SR	reddish	medium-to coarse-grained; poorly to well cemented by limonite	Mio.? of N. Coronado Id.	
Sandstone (cgl.)	2	5	A	gn.	chloritized; some glaucophane; medium-grained	Franciscan (Jur.?) prob. from Mio. cgl.	
Limestone	1	9	A	dk. gy.	crystalline		
2. Scr. 9381—Lat. 32°30.5′, Long. 117°18.6′; 948 feet; dredge; Coronado Canyon—south wall; transported							
Andesite	3	5	A	gy.-buff	porphyritic		
Sandstone	1	4	SR	reddish	medium-grained; limonite cement	Mio.? of N. Coronado Id.	
Limestone	1	4	A	white	noncrystalline—shelly		
3. Scr. 9384—Lat. 32°31.0′, Long. 117°20.5′; 816? feet; dredge; Coronado Canyon—south wall; shale and sandstone outcrop							
Quartzite (cgl.)	2	10	A-SA	gn. and gy.	dark layers	Franciscan (Jur.?) prob. from Mio. cgl.	
Shale	39	8	A	gy.	well consolidated	Mio.? of S. Coronado Id.	
Sandstone	29	61	A	yel. gy.	coarse-grained; poorly cemented; freshly broken	Mio.? of S. Coronado Id.	

* Conclusion as to whether sample was obtained from outcrops or was transported is based on criteria given in text.

Sandstone	2	4	A-SA	lt. gy.	medium-grained; poorly cemented by $CaCO_3$		
5. Scr. 9583—Lat. 32°39.2′, Long. 117°25.5′; 510 feet; corer; Bank southwest of San Diego							
Volcanic	2	0.3	A	gn.	fine-grained		
Phosphorite	6	0.7	A-SR	br.-bk.	homogeneous		
6. Scr. 9584—Lat. 32°39.2′, Long. 117°25.5′; 510 feet; snapper; Bank southwest of San Diego							
Metavolcanic (cgl.)	1	4	SR	gy.-br.	anhedral feldspar phenocrysts	Black Mtn. (Tri.-Jur.) prob. from Eo. cgl.	
Limestone	1	4	A	gy.	finely crystalline		
7. Scr. 8531—Lat. 32°44.5′, Long. 117°20.8′; 420 feet; snapper; Shelf south of La Jolla							
Metavolcanic (cgl.)	1	2	SA	gy.	finely crystalline quartz groundmass	Black Mtn. (Tri.-Jur.) prob. from Eo. cgl.	
8. Scr. 8528—Lat. 32°45.8′, Long. 117°21.5′; 570 feet; snapper; Shelf south of La Jolla; probably at outcrop							
Metavolcanic (cgl.)	25	2	A-SA	dk. gy.	porphyritic	Black Mtn. (Tri.-Jur.) prob. from Eo. cgl.	
Sandstone	1	2	A	lt. gy.	fine-grained; $CaCO_3$ cement		
9. FPS 61—Lat. 32°48.6′, Long. 117°20.0′; 162 feet; dredge; Shelf south of La Jolla; outcrop							
Sandstone	60	28	A	gy.	well cemented by $CaCO_3$; freshly broken	Chico (Cret.) or Rose Canyon (Eo.)	
Shale	40	10	A	dk. gy.	compact; plant material	Chico (Cret.) or Rose Canyon (Eo.)	Eocene (Foraminifera)
10. FPS 25—Lat. 32′51.5′, Long. 117°15.8′; 180 feet; corer; La Jolla Canyon—east head; transported							
Metavolcanic (cgl.)	1	5	R	reddish	subhedral phenocrysts	Black Mtn. (Tri.-Jur.) prob. from Eo. cgl.	

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
11. *LJ 5—Lat. 32°51.3′, Long. 117°16.2′; 60? feet; dredge; La Jolla Canyon—west head; outcrop*							
Shale	30	10	A	bu. gy.	compact; sandy bands	Chico (Cret.)	Cret. or Eo. (Foraminifera)
12. *FPS 23—Lat. 32°51.4′, Long. 117°16.3′; 210 feet; dredge; La Jolla Canyon—west wall; outcrop*							
Shale	25	45	A	bu. gy.	compact; plant fossils; freshly broken	Chico (Cret.)	Cret. or Eo. (Foraminifera) Cret. (baculites)
13. *FPS 22—Lat. 32°51.5′, Long. 117°16.3′; 150 feet; dredge; La Jolla Canyon—west wall; transported*							
Metavolcanic (cgl.)	1	2	SA	lt. gy.	soft; weathered	Black Mtn. (Tri.-Jur.) prob. from Eo. cgl.	
Shale	1	3	SA	bu. gy.	compact	Chico (Cret.)	
14. *LJ 3—Lat. 32°51.6′, Long. 117°16.4′; 300–600? feet; dredge; La Jolla Canyon—west wall; Eocene outcrop*							
Metavolcanic (cgl.)	43	8	SR-R	dk. gy.	loose cobbles from cgl.	Black Mtn. (Tri.-Jur.) prob. from Eo. cgl.	
Conglomerate	15	8	SA	br.	poorly cemented ss. enclosing cobbles of Black Mtn. metavolc.	Rose Canyon (Eo.)	
Shale	30	17	A	bu. gy.	compact	Chico (Cret.)	Cret. or Eo. (Foraminifera)
15. *LJ 4—Lat. 32°51.8′, Long. 117°16.4′; 600? feet; dredge; La Jolla Canyon—east wall; outcrop*							
Metavolcanics (cgl.)	13	9	R	gy.		Black Mtn. (Tri.-Jur.)	
Sandstone (cgl.)	11	5	A	br.	very loosely cemented	prob. from Eo. cgl.	

Conglomerate	60	11	A		poorly cemented ss. enclosing cobbles of Black Mtn. metavolc.	Rose Canyon or Poway (Eo.)	
17. FPS 140—Lat. 32°52.1′, Long. 117°16.7′; 840 feet; corer; La Jolla Canyon—middle; probably at outcrop							
Shale	50?	4	A	dk. gy.	very soft, lumpy	Eo. or Cret.	
18. FPS 146—Lat. 32°52.9′, Long. 117°17.0′; 1080 feet; dredge; La Jolla Canyon—outer axis; outcrop							
Sandstone	30	20	A	gy.	crumbly to well cemented	Eo. or Cret.	
Shale	2	5	A	gy.	sandy	Eo. or Cret.	
19. FPS 147—Lat. 32°53.2′, Long. 117°19.0′; 1560 feet; dredge; La Jolla Canyon—outer south wall; mudstone outcrop							
Schist (cgl.)	4	7	SA	bu. gy.	quartz-chlorite		
Schist (cgl.)	1	2	SA	bu. gy.	quartz-glaucophane	Franciscan (Jur.?) prob. from Mio. cgl.	
Granite gneiss (cgl.)	1	2	SA	white			
Metavolcanic	5	7	SA	dk. gy.	plagioclase porphyry		
Sandstone	6	7	A	gy.	medium-grained; $CaCO_3$ cement; broken mollusk shells		Tertiary (mollusks)
Mudstone	41	13	A	gy.	laminated; opal in joints	Miocene	u.(?) Mio. (Foraminifera)
Phosphorite	1	3	SR	br.	homogeneous	Miocene?	
20. Scr. 6413—Lat. 32°05.8′, Long. 117°21.2′; 294 feet; corer; Shelf south of Carlsbad Canyon; transported							
Metavolcanic (cgl.)	2	2	SA	gn.-gy; br.	originally granodiorite(?)	Black Mtn.? (Tri.-Jur.) prob. from Eo. cgl.	
21. FPS 137—Lat. 33°06.7′, Long. 117°22.3′; 312–780 feet; dredge; Head of Carlsbad Canyon; transported							
Granite (?)	10	0.5	SA-SR	lt. gy.	coarse-grained		
Metavolcanic (cgl.)	4	0.5	SA	gn.-gy.	schistose	Black Mtn. (Tri.-Jur.) prob. from Eo. cgl.	

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
22. FPS 320—Lat. 33°38.5′, Long. 118°12.0′; 54 feet; dredge; Shelf in San Pedro Bay; probably at outcrop							
Limestone	1	45	A	white	cherty; laminated; brown layers	Miocene	
23. FPS 37—Lat. 33°39.0′, Long. 118°16.8′; 720 feet; dredge; San Pedro Seavalley—head; near limestone outcrop							
Sandstone	1	2	A	buff	hydrothermal alteration		
Limestone	7	30	A-SR	dk. gy.	crystalline, one with kelp holdfast attached, borings		
Limestone	3	7	SA-SR	lt. gy.-tan	shell fragments		
Opal joint filling	1	3	A	white	around block of limestone		
24. FPS 33—Lat. 33°39.5′, Long. 118°16.9′; 720 feet; dredge; San Pedro Seavalley (north branch); mudstone outcrop							
Mudstone	25+	35+	A	gy.	soft; no bedding planes		l. Pliocene (Foraminifera) Mio.-Plio. (Mollusks)
Limestone	1	2	A	gy.	crystalline (kelp holdfast attached)		
24A. Varney-Redwine (1937)—Lat. 33°40.2′, Long. 118°18.2′; 300 feet; corer; San Pedro Seavalley (lip of north branch) outcrop							
Mudstone				br.	diatoms and Radiolaria	u. Miocene	u. Miocene
25. FPS 290—Lat. 33°38.3′, Long. 118°18.3′; 1800–2220 feet; small dredge; San Pedro Seavalley—bottom; outcrop?							
Mudstone	6	2	A	gy.	soft—a few nondiagnostic diatoms		
26. FPS 90—Lat. 33°38.8′, Long. 118°20.4′; 2286 feet; corer; San Pedro Seavalley—bottom; transported							
Granite	11	0.8	SR	white			
Limestone	6	0.3	A	gy.	finely crystalline		

Meta-rhyolite	3	7	A-SR	gy.	high quartz content		
Limestone	4	6	A	dk. gy.	crystalline	Miocene	
Phosphorite	86	16	A-SA	dk. br.-gy.	glauconite; coprolites; Foraminifera	Miocene?	
28. FPS 128—Lat. 33°48.2′, Long. 118°29.1′; 1470 feet; dredge; Redondo Canyon—south wall; transported							
Granite	1	3	SR	lt. gy.	very little orthoclase		
29. FPS 87—Lat. 33°49.1′, Long. 118°31.5′; 570 feet; corer; Redondo Canyon—north wall							
Limestone	2	5	A	gy.; br.	diatomaceous	Miocene	
Phosphorite	1	3	SA	dk. br.	coprolites	Miocene?	
30. FPS 129—Lat. 33°48.4′, Long. 118°31.7′; 1680 feet; dredge; Redondo Canyon—north wall; outcrop							
Mudstone	30	14	A	gy.	abundant Foraminifera in bands	Miocene	l. u. Miocene (Foraminifera)
31. FPS 86—Lat. 33°48.2′, Long. 118°30.2′; 810 feet; dredge; Redondo Canyon—south wall; outcrop							
Mudstone	5	10	A	dk. gy.	diatomaceous	Miocene	u.m. Miocene (diatoms)
Limestone	100+	7	A	dk. gy.	crystalline; diatoms common		
Bone	1	2	A	br.	phosphatized		
32. FPS 303—Lat. 33°53.7′, Long. 118°34.4′; 240 feet; dredge; Santa Monica shelf; sedimentary rock outcrop							
Basalt	2	24	A	bk.-br.	pilitic; ophitic		
Andesite	1	4	A	br.	porphyritic		
Mudstone	20	4	A	gy.	soft; mostly diatomaceous	Miocene	
Limestone	27	32	A-SA	gy.-br.	crystalline; hard; thinly bedded	Miocene	
Limestone	3	60	A	white	cherty	Miocene	
Limestone	10	10	A	bk.	bituminous; large calcite crystals		
Chert	3	8	A-SA	bk.	white surface alteration	Miocene	
Phosphorite	50	15	SR	bk.	mostly oölitic	Miocene?	m. Miocene (Foraminifera)

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
33. FPS 103—Lat. 33°55.0′, Long. 118°33.2′; 300 feet; dredge; Santa Monica Canyon—head; transported							
Granite	85	16	SA-R	white	abundant orthoclase and albite	Jurassic?	
Quartz	3	4	R	white	from pegmatite?		
Rhyolite	1	4	A	red	very fine-grained		
Slate	1	2	SA	bk.	fine cleavage		
Metasandstone	1	3	SA	dk. gy.	quartz grains in chlorite		
Shale	7	4	SR	yel.	tuffaceous; contains chert bands	Miocene	
Limestone	2	18	A	gy.	chert enclosed	Miocene	
Chert	7	19	A-R	bk.	white surface alteration	Miocene	
Phosphorite	2	2	SR	dk. br.	one massive, other conglomeratic	Miocene?	
34. FPS 101—Lat. 33°55.0′, Long. 118°34.6′; 900 feet; dredge; Santa Monica Canyon—south wall; sedimentary rock outcrop							
Granodiorite	1	3	SR	gy.	coarse-grained		
Shale	2	7	SA	yel. gy.	sandy; quartz, biotite, Foraminifera		l.u. Miocene (Foraminifera)
Limestone	1	5	SA	gn. gy.	finely crystalline		
Limestone concretions	3	13	SR	gy.	crystalline; botryoidal calcite core		
35. FPS 106—Lat. 33°54.5′, Long. 118°36.3′; 540 feet; dredge; Santa Monica Canyon—south wall; limestone and phosphorite outcrop							
Granite	1	7	A	gy.	coarse-grained		
Conglomerate	1	4	A	white & br.	calcite cementing coprolites and phosphorite		u. Plio. or Quat. (Foraminifera)
Limestone	3	13	A	gy.	finely crystalline	Miocene	
Phosphorite	28	52	A-SA	br.-bk.	glauconite; coprolites	Miocene?	Miocene (Foraminifera)
36. FPS 108—Lat. 33°59.0′, Long. 118°39.6′; 600 feet; dredge; Santa Monica Canyon—north wall							
Shale	1	9	A	gy.	cherty; compact	Miocene	

Basalt	15	5	A	gy.-br.	weathered; fresh fractures		
38. FPS 115—Lat. 33°59.3′, Long. 118°48.5′; 780 feet; small dredge; Dume Canyon—west wall; mudstone outcrop							
Mudstone	40	7	A	lt. gy.	diatomaceous	Miocene	u.m. Miocene (diatoms)
Phosphorite	1	2	SA	br.	granular		
39. FPS 112—Lat. 33°58.6′, Long. 118°48.0′; 1380 feet; dredge; Dume Canyon—east wall; sedimentary rock outcrop							
Dacite	1	6	SR	bk.			
Limestone	75	60	A	gy.	crystalline; concretionary; mollusks	Miocene?	
40. FPS 111—Lat. 33°58.5′, Long. 118°48.8′; 1440 feet; dredge; Dume Canyon—west wall; transported							
Granite	1	13	SA	dk. gy.	coarse-grained; biotite		
41. FPS 119—Lat. 34°04.5′, Long. 119°05.5′; 912 feet; corer; Mugu Canyon—northeast wall; outcrop							
Sandstone	1	4	A	gy.	calcite cement; freshly broken		
42. FPS 305—Lat. 34°04.7′, Long. 119°06.5′; 930 feet; corer; Mugu Canyon—center; probably at outcrop							
Sandstone	6	5	A	gy.	highly arkosic; chlorite and calcite cement		
43. FPS 124—Lat. 34°01.2′, Long. 119°03.4′; 1080 feet; dredge; Slope of bank east of Mugu Canyon; probably at outcrop							
Shale	1	20	A	white	cherty; freshly broken	Miocene	
44. FPS 125—Lat. 34°01.1′, Long. 119°02′; 282 feet; dredge; Bank east of Mugu Canyon							
Chert	1	6	A	bk.	surface altered to gy.	Miocene	
45. FPS 126—Lat. 34°00.0′, Long. 119°01.5′; 282 feet; dredge; Bank east of Mugu Canyon; outcrop							
Limestone	14	35	A	gy.	crystalline	Miocene?	

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
46. FPS 308—Lat. 34°08.1', Long. 119°13.5'; 468 feet; corer; Hueneme Canyon—head; transported							
Granite	13	4	SA-SR	white, gy., red	many more less than 1 cm. dia.		
Sandstone	11	5	SA-SR	br.-gn.			
Shale	3	1.5	SR		cherty	Miocene	
47. FPS 307—Lat. 34°08.1', Long. 119°13.5'; 432 feet; corer; Hueneme Canyon—head; transported							
Granite	1	0.8	SR	white			
48. FPS 260—Lat. 34°06.7', Long. 119°14.0'; 930 feet; corer; Hueneme Canyon— bottom; transported							
Granite	1	2	SA	white	coarse-grained		
49. FPS 313—Lat. 34°05.1', Long. 119°14.0'; 1272 feet; corer; Hueneme Canyon—bottom; transported							
Granite	4	0.6	SR	white, dk. gy.			
Diorite?	1	0.3	R	dk. gy.	very fine-grained		
Shale	1	0.5	SR	buff	cherty; banded	Miocene	
50. FPS 268—Lat. 32°04.5', Long. 118°14.5'; 390 feet; dredge; Sixtymile Bank; probably near outcrop							
Schist	3	9	A	gn.	albite-mica schist and crossite schist	Franciscan (Jur.?)	
51. FPS 269—Lat. 32°04.3', Long. 118°14.5'; 360 feet; dredge; Sixtymile Bank							
Schist	1	2	A	lt. gn.	albite-quartz-chlorite	Franciscan (Jur.?)	
52. FPS 272—Lat. 32°21.8', Long. 118°17.5'; 1080 feet; dredge; Hill 15 miles north of Sixtymile Bank; outcrop							
Schist	25	68	A	gn.	chlorite-albite	Pelona? (P-Cambrian)	

53. FPS 266—Lat. 32°16.6′, Long. 117°32.5′; 2310 feet; dredge; Hill southeast of Thirtymile Bank; outcrop							
Andesite	50	28	A	yel.	porphyritic; weathered; some fragments cemented by manganese oxide		
54. Scr. 9589—Lat. 32°39.3′, Long. 117°43.1′; 1158 feet; snapper; Thirtymile Bank—south end							
Andesite	2	8	SA	lt. to dk. gy.	andesine-augite porphyry		
55. FPS 64—Lat. 32°46′, Long. 117°46′; 1020 feet; dredge; Thirtymile Bank—east slope; transported							
Andesite	1	20	R	lt. gy.	porphyritic		
Phosphorite	1			br.	fills pholad borings in andesite		u. Plio, or Quat. (Foram.)
56. FPS 65—Lat. 32°48′, Long. 117°47.8′; 1170 feet; dredge; Thirtymile Bank—east slope; probably near schist outcrop							
Quartz	1	6	A	white; br.	from pegmatite?		
Basalt	1	13	SA	dk. gy.	olivine altered		
Andesite	1	30	A	dk. gy.	glomeroporphyritic		
Rhyolite	1	17	R	br. gy.	microcrystalline; sediment line well shown		
Schist	9	7	A	white-lt. gn.	albite-chlorite-epidote	Franciscan (Jur.?)	
Sandstone	1	7	A	lt. br.	calcite cement		
Phosphorite	1	5	A		conglomerate; quartz; mudstone pebbles		m. Miocene (Foraminifera)
57. FPS 66—Lat. 32°48.5′, Long. 117°47.2′; 2700 feet; dredge; Thirtymile Bank—east slope; transported							
Andesite	100	0.5	SA	gy.	coarse sand grains		

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
58. *FPS 63—Lat. 32°43.7′, Long. 117°47.8′; 1260 feet; dredge; Thirtymile Bank—west side; probably near sedimentary rock outcrop*							
Andesite	1	14	SA	dk. gy.	hydrothermally altered		
Limestone	1	15	SA	lt. br.	shaly, bedded		
Chert	4	14	SA	bk.	bedding planes	Miocene	
Phosphorite cgl	6	25	A	br.	includes pebbles of phosphorite, ls., andesite, schist, chert, qtz.	Miocene? nodules	nodules: m. Miocene; matrix., u. Plio. or Quat. (Foraminifera)
Phosphorite	6	14	SA	br.	mostly homogeneous		Miocene? (Foraminifera)
59. *FPS 62—Lat. 32°43.8′, Long. 117°48.5′; 960–1200 feet; dredge; Thirtymile Bank—west side; transported*							
Andesite-basalt	25	0.1	A	dk. gy.-br.			
Schist	10	0.1	A	white-gn.	crossite-albite	Franciscan (Jur.?)	
60. *Scr. 9496—Lat. 32°37.0′, Long. 117°49.5′; 2610 feet; corer; Trough west of Thirtymile Bank; near phosphorite outcrop*							
Granite?	1	1	A	white	fine-grained		
Andesite	1	1	A-SR	gy.	porphyritic; hydrothermal alteration		
Phosphorite	35	2	A	lt.-dk. br.	coprolites; Foraminifera	Miocene?	
61. *Scr. 9591—Lat. 32°39.4′, Long. 117°54.9′; 1326 feet; snapper; Fortymile Bank—east slope; transported*							
Phosphorite	1	0.6	A	br.	glauconite		

62. *FPS 69—Lat. 32°37.0′, Long. 117°56.2′; 600 feet; dredge; Fortymile Bank—south side; outcrop*

Phosphorite	2	32	SR	br.	five major growth layers which enclose older nodules, 1 pebble of rhyolite, 3 of crossite schist, oölites, glauconite	Miocene?	nodules: m. Miocene layers: u. Plio. or Quat. (Foraminifera)

63. *FPS 51—Lat. 32°39.3′, Long. 117°57.5′; 342 feet; dredge; Fortymile Bank—top; quartzite outcrop*

Andesite	2	7	A	gy.	scoriaceous		
Quartzite	10	50	A	gy.-purplish	banded; freshly broken	Franciscan? (Jur.?)	

64. *FPS 52—Lat. 32°39.7′, Long. 117°57.8′; 342–372 feet; dredge; Fortymile Bank—top; transported*

Andesite	3	5	SA-R	dk. gy.	porphyritic; scoriaceous; glassy		

65. *FPS 16—Lat. 32°39.5′, Long. 117°58.5′; 300 feet; dredge; Fortymile Bank—top; transported*

Basalt	12	12	SA-SR	gy.	porphyritic to trachytic to aphanitic; massive to scoriaceous; some olivine		
Andesite	23	12	SA-SR	yel.-gy.	porphyritic to trachytic; massive to scoriaceous; augite and plagioclase phenocrysts		
Breccia, volcanic	2	8	SA-SR	reddish	angular fragments of andesite		
Slate	1	3	A	bk.	slightly wavy laminations		
Sandstone	1	5	SR	gn.	slickensided?		
Shale	3	15	SA	yel.-gy.	finely laminated, cherty	Miocene	
Tuff	1		R		coarse-grained; soft		
Limestone	1	5	SR	bk.	dense; hard		
Phosphorite	6	3	SA-SR	br.	coprolites; Foraminifera	Miocene?	l.m. Miocene (Foraminifera)

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
66. *FPS 53—Lat. 32°39.4′, Long. 117°59.2′; 390–600 feet; dredge; Fortymile Bank—top; transported*							
Basalt	1	3	A	br.	aphanitic; olivine altered		
Andesite	4	4	SA	gy.-yel.	3 plagioclase porphyries; 1 augite porphyry		
Quartzite	1	7	SR	yel.	quartz grains recrystallized		
Sandstone	1	6	SA		friable; calcite cement		
Limestone	1	3	A	lt. gy.	crystalline		
Chert	1	6	SR	dk. gy.	incipient crystals	Miocene	
67. *FPS 70—Lat. 32°39.5′, Long. 118°01.0′; 1800 feet; dredge; Northwest slope of Fortymile Bank; phosphorite and tuff outcrop*							
Andesite	2	5	A	br.	glomeroporphyritic		
Schist	2	10	A	gn.	chlorite-quartz-albite	Franciscan (Jur.?)	
Tuff	50	10	A	white	friable, bedded, siliceous		
Phosphorite	100	22	A	br.	banded, oölitic	Miocene?	m. Miocene (Foraminifera)
68. *Pio. 6—Lat. 32°42.0′, Long. 118°06.8′; 1608 feet; snapper; Northwest slope of Fortymile Bank*							
Mudstone	1	1	A	gy.	unfossiliferous, sandy		
Phosphorite	2	1.5	A	br.	glauconite, coprolites	Miocene?	
69. *FPS 48—Lat. 32°41.5′, Long. 118°07.7′; 1800–2400 feet; dredge; Northwest slope of Fortymile Bank; sedimentary rock outcrop*							
Granite	1	3	SR	gy.	coarsely crystalline		
Quartz	4	3	S-SR	white	from pegmatite?		
Basalt	1	4	SR	dk. gy.	trachytic		
Andesite	9	22	A-R	gy.-br.	porphyritic; massive to scoriaceous		
Rhyolite	2	4	A-SR	br.			
Slate	2	2	A	dk. gy. gn.	platy; wavy laminations		—

Schist	1	3	A	yel. gy.	glaucophane; highly altered hydrothermally	Franciscan (Jur.?)	
Quartzite	1	17	SR	dk. gy.	fractured		
Sandstone	1	5	A	dk. gy.	calcite cementing rock grains		
Mudstone	4	10	A	gy.	bands of Foraminifera	Miocene	l.u. Miocene (Foraminifera)
Tuff	2	5	SA-SR	white	green at surface		
Limestone	15	7	A-SA	buff	shaly		u. Miocene (Foraminifera)
Limestone	3	60	A	yel.	crystalline; hard		
Opal	9	6	A	bu.	irregular; crack fillings		
Phosphorite	300	30	A	br.	bones, glauconite, coprolites	Miocene?	u.m. Miocene (Foraminifera)

70. *FPS 71—Lat. 32°43.3′, Long. 118°09.0′; 2460 feet; dredge; Northwest slope of Fortymile Bank; phosphorite outcrop?*

Quartz	2	1	SR-R	white	cracks contain collophane		
Basalt	2	6	SA	dk. gy.	ophitic		
Andesite	33	10	A-R	gy.-br.	porphyritic to trachytic scoriaceous to glassy		
Rhyolite	9	6	A-R	gy.-br.	hydrothermal alteration		
Schist	15	7	A-R	gn.	1 actinolite; 1 glaucophane; 13 chlorite-albite	Franciscan (Jur.?)	
Limestone	35	12	SA-SR	lt. gn.-lt. br.	mostly shaly	Miocene?	
Phosphorite	461	15	A-SA	br.-gy.	shaly to dense, bones, teeth	Miocene?	m. or u. Miocene (Foraminifera)

71. *FPS 45—Lat. 32°47.1′, Long. 118°15.7′; 3600 feet; dredge; "Rift" Valley—northeast wall; sedimentary rock outcrop*

Basalt	4	30	A-SA	dk. gy.	pilitic; amygdular		
Andesite	11	25	A-SR	gy.-yel.	plagioclase and augite porphyry; massive to scoriaceous; weathered		

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
71. FPS 45—Lat. 32°47.1′, Long. 118°15.7′; 3600 feet; dredge; "Rift" Valley—northeast wall; sedimentary rock outcrop—Continued							
Rhyolite	3	23	A-SA	yel.-white	holocrystalline		
Meta-volcanic	1	9	R	gn.	massive, glass?	Franciscan? (Jur.?)	
Mudstone	50	45	A	gy. gn.	soft; loosely consolidated		l.u. Miocene (Foraminifera)
Spiculate	1	10	A	buff	hard; porous; very abundant, sponge spicules and diatoms		
Limestone	6	10	A	buff	3 marly; 3 dense crystalline		
Phosphorite	6	30	A-SA	br.	layered; glauconite, Foraminifera, bones	Miocene?	u. Miocene (Foraminifera)
72. FPS 43—Lat. 32°46.5′, Long. 118°16.5′; 3780 feet; dredge; "Rift" Valley—southwest wall; outcrop							
Limestone	8	18	A-SA	buff	fresh fracture; shaly to cherty	Miocene	u.? Miocene (Foraminifera)
73. FPS 11—Lat. 32°46.8′, Long. 118°16.4′; 4200 feet; corer; "Rift" Valley—southwest wall; outcrop							
Shale	10	4	A	bk.	layers; jointed		
Chert	10	2	A	gy.-bk.	layered	Miocene	u.? Miocene (Foraminifera)
74. FPS 47—Lat. 32°47.3′, Long. 118°17.8′; 2700 feet; dredge; "Rift" Valley—southwest wall; outcrop							
Sandstone	1	20	SA	lt. gy.	grains poorly sorted		
Mudstone	50	25	A	gy.	soft; Foraminifera in bands	Miocene	m. Miocene (Foraminifera)
Limestone	5	30	A	lt. gy.		Miocene	
Chert	2	30	A	bk.	interbedded with shale	Miocene	m.? Miocene (Foraminifera)

Phosphorite	3	1	A	br.	sand cemented by collophane		
76. FPS 40—Lat. 32°47.6′, Long. 118°17.8′; 3630 feet; dredge; "Rift" Valley—northeast wall; sedimentary rock outcrop							
Basalt	1	4	SA	dk. gy.	glassy groundmass		
Breccia	200	30	A	br.	chert; sandstone; in very soft matrix		
Sandstone	32	25	A-SA	gy.	medium to coarse grains of quartz and feldspar		
Sandstone	2	3	SA	dk.-lt. gy.	shell fragments and rock grains		
Mudstone	5	5	A	lt. gy.	some show contact with sandstone	Miocene	l.u. Miocene (Foraminifera)
Shale	3	4	A	lt. br.	concentric layers of limonite		
Limestone	9	5	A	white-gy.	shaly; veins of calcite; soft		
Limestone	5	30	A	bk.	crystalline	Miocene?	
Chert	150	12	A	tan-bk.	partly layered	Miocene	m. Miocene (Foraminifera)
Chert	4	15	A	bk.; white	chert-weathered, brecciated	Miocene	
77. Pio. 8—Lat. 32°46.7′, Long. 118°18.7′; 1656 feet; snapper; "Rift" Valley—southwest wall							
Phosphorite	1	2	A	br.	homogeneous		
78. FPS 72—Lat. 32°48.3′, Long. 118°19.0′; 1890 feet; dredge; Slope northeast of San Clemente Island							
Andesite	3	4	A	gy.	plagioclase porphyry; one piece highly altered		
79. Pio. 14—Lat. 32°48.6′, Long. 118°18.6′; 2424 feet; snapper; Slope northeast of San Clemente Island							
Andesite	1	1	A	gy.	plagioclase porphyry		
80. FPS 7—Lat. 32°49.0′, Long. 118°19.2′; 2100 feet; dredge; Slope northeast of San Clemente Island							
Andesite	1	1	A	yel.	plagioclase porphyry, weathered; fresh fractures		
Phosphorite	1	2	A	br.	granular		

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
81. FPS 58—Lat. 32°50.5′, Long. 118°21.0′; 1692 feet; corer; Slope northeast of San Clemente Island; probably transported							
Andesite	1	2	SA	dk. gy.	augite-plagioclase porphyry		
82. FPS 60—Lat. 32°50.0′, Long. 118°21.0′; 1650 feet; dredge; Slope northeast of San Clemente Island; near andesite outcrop							
Basalt-andesite	1	3	A	gy.	altered		
Andesite	156	35	A-R	dk. gy.-yel.	plagioclase-augite porphyry, massive to scoriaceous		
Rhyolite	2	5	SR	lt. gy.-gy. gn.	small irregular masses of quartz		
Breccia	2	5	A	lt. gn.	angular andesite; organic remains in matrix		
Sandstone	5	15	A-R	dk. gy.	calcite cement, Foraminifera		
Mudstone	2	2		br.	soft; high organic content		
Shale	1	4	A	lt. gn.	bedded; hard; calcareous		
Tuff	3	9	SA	lt. gn.	weathered; soft; sandy		
Chert	1	3	A	br.	Foraminifera	Miocene	Miocene (Foraminifera)
83. FPS 59—Lat. 32°50.1′, Long. 118°20.1′; 2790 feet; dredge; Slope northeast of San Clemente Island							
Andesite	2	6	A	dk. gy.	1 fresh; other hydrothermally altered		
84. FPS 6—Lat. 32°51.2′, Long. 118°20.8′; 2100–2580 feet; dredge; Slope northeast of San Clemente Island; concretions and mudstone at outcrop							
Andesite	6	10	A	dk. gy.	plagioclase porphyry		
Barite concretions	250	25		lt. gy.	sediment cemented by barite		l. Pliocene (Foraminifera)
Mudstone	50 kg.			lt. gy.	soft; unconsolidated, no bedding		l. Pliocene (Foraminifera)

85. *FPS 57—Lat. 32°51.1′, Long. 118°22.0′; 1560 feet; corer; Slope northeast of San Clemente Island; transported*							
Andesite	6	1.5	SA	dk. gy.	augite porphyry		
Dacite	1	0.5	SA	buff	quartz crystals		
86. *FPS 56—Lat. 32°51.6′, Long. 118°21.4′; 2244 feet; corer; Slope northeast of San Clemente Island; transported*							
Andesite	15	1.5	A-SA	dk. gy.	plagioclase porphyry; scoriaceous		
87. *FPS 8—Lat. 32°54.0′, Long. 118°24.6′; 2400 feet; dredge; Slope northeast of San Clemente Island; outcrop*							
Mudstone	10	6	A	dk. gy.	soft; no bedding observed		l. Pliocene (Foraminifera)
88. *Scr. 9596—Lat. 32°45.0′, Long. 118°24.0′; 566 feet; snapper; Slope southeast of San Clemente Island; probably transported*							
Meta-sediment	1	8	SA	gn.	serpentinized		
89. *Scr. 9602—Lat. 32°38.0′, Long. 118°38.0′; 3228 feet; corer; Small elevation southwest of San Clemente Id.; probably near outcrop*							
Sandstone	60	1.5	A	br.	plagioclase and andesite cemented partly by phosphorite		
Mudstone	1				soft		l. Pliocene (Foraminifera)
Phosphorite	20	1	SR	br.	glauconite, Foraminifera, coprolites		
90. *Pio 57—Lat. 32°42.4′, Long. 118°37.0′; 2952 feet; snapper; Small elevation southwest of San Clemente Id.*							
Andesite	1	1.5	A	gn. gy.	pilitic		
91. *FPS 285—Lat. 33°01.8′, Long. 118°23.0′; 2310 feet; dredge; Elevation in Catalina Basin*							
Rhyolite	4	8	SA	br.	porphyritic		
92. *Scr. 6414—Lat. 33°07.5′, Long. 117°52.0′; 1890 feet; dredge; Hill in San Diego Trough; outcrop*							
Andesite	104	7	A	gy.	scoriaceous; plagioclase laths		

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
93. FPS 288—Lat. 33°23.9′, Long. 118°00.0′; 450 feet; small dredge; Hill in San Diego Trough							
Andesite	1	0.2	SA	dk. gy.	porphyritic		
Limestome	1	2	A	white	finely crystalline		
Limestone	3	0.5	A	br.	phosphatic		
94. FPS 289—Lat. 33°23.9′, Long. 118°00.0′; 450 feet; small dredge; Hill in San Diego Trough							
Schist	1	0.5	A	bu. gy.	quartz-crossite	Franciscan (Jur.?)	
Sandstone	2	0.5	A	gy.-bk.	quartz; chlorite; glauconite		
Limestone	13	1.5	A	lt. gy.	finely crystalline	Miocene?	
Limestone	7	1	A	lt. gy.	phosphatic		
95. FPS 76—Lat. 33°28.0′, Long. 118°30.3′; 276 feet; corer; Northwest end of Catalina Id.; transported							
Schist	5	0.2	A	gn.	albite-quartz-chlorite	Franciscan (Jur.?)	
96. Scr. 6424—Lat. 33°29′, Long. 118°30′; 882 feet; corer; Northwest end of Catalina Id.; transported							
Andesite	10	1	SA	br.	plagioclase porphyry		
Schist	40	1.5	A-R	gn.	quartz-albite-chlorite	Franciscan? (Jur.?)	
Quartzite	5	1	SR-R	white	fractured		
97. FPS 75—Lat. 33°27.0′, Long. 118°35.9′; 300 feet; corer; Northwest end of Catalina Id.; transported							
Phosphorite	1	0.2		br.			
Schist	100?	0.2	A	gn.	albite-quartz-chlorite	Franciscan (Jur.?)	
98. Scr. 9648—Lat. 33°19.8′, Long. 119°01.0′; 1410 feet; corer; South of Santa Barbara Id.							
Basalt-Andesite	12	0.6	A	br.-yel.	plagioclase porphyry; scoriaceous		
Phosphorite	1	2	A	br.-bk.	unidentifiable Foraminifera		

99. *Scr. 6437—Lat. 33°44.0′, Long. 119°06.5′; 2460 feet; corer; Northwest of Santa Barbara Id.; transported*

Basalt	2	4	A-SR	bu. gn.	plagioclase porphyry; holocrystalline		

100. *Scr. 9610—Lat. 33°25.0′, Long. 119°03.5′; 282 feet; snapper; Cortes Bank; transported*

Phosphorite	2	1	A-SR	br.	Foraminifera; coprolites		m.? Miocene (Foraminifera)

101. *FPS 276—Lat. 32°25.1′, Long. 119°07.4′; 312 feet; dredge; Cortes Bank; transported*

Basalt	3	1.5	SR	dk. gy.	porphyritic; olivine altered		
Mudstone	1	3	SR	lt. gy.	soft; friable; unfossiliferous		
Mudstone	1	0.3	A	lt. gy.	soft; abundant diatoms, radiolarians	Miocene?	mixed u.m. Miocene and Recent (diatoms)

102. *Scr. 9656—Lat. 32°25.1′, Long. 119°02.2′; 216 feet; snapper?; Cortes Bank; transported*

Basalt	6	1.5	A	dk. gy.	plagioclase porphyry; some olivine		

103. *FPS 275—Lat. 32°26.4′, Long. 119°06.0′; 66 feet; dredge; Cortes Bank; outcrop*

Basalt	15	10	A		plagioclase and augite porphyry; ophitic; olivine altered; fresh fractures		

104. *FPS 277—Lat. 32°28.2′, Long. 119°12.4′; 72 feet; dredge; Cortes Bank*

Basalt	2	3	A	orange-red	plagioclase-augite porphyry; ophitic; olivine altered		

105. *FPS 281—Lat. 32°42.0′, Long. 119°06.2′; 96 feet; dredge; Tanner Bank*

Basalt-andesite	3	6	A	br.	olivine altered		

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
106. *FPS 283—Lat. 32°35.0′, Long. 119°04.0′; 1890 feet; corer; Tanner Canyon; outcrop*							
Mudstone	100	4	A	bk.	soft; freshly broken		l.m. Miocene (Foraminifera)
Limestone	1	1.5	A	lt. gy.	shelly; noncrystalline		
Phosphorite	10	2	A	lt.-dk. br.	oölitic		
107. *FPS 273—Lat. 32°29.5′, Long. 118°41.0′; 1650 feet; dredge; Elevation southeast of Tanner Bank*							
Andesite	5	18	R		plagioclase porphyry		
Rhyolite	1	8	SR	gn. gy.	holocrystalline		
Dacite	1	3	A	lt. br.	quartz enclosing plagioclase laths		
Sandstone	1	2	A		coarse grains of quartz and andesine cemented by $CaCO_3$		
Mudstone	6	6		gn.	soft; loosely consolidated		mixture of l. Miocene to l. Pliocene (Foraminifera)
Limestone	4	14	SA	br.	hard; crystalline	Miocene	
Phosphorite	10	4	SA	br.	layers; glauconite; oölites	Miocene?	
108. *Scr. 9604—Lat. 32°35.0′, Long. 118°44.5′; 3280 feet; corer; Elevation southeast of Tanner Bank; transported*							
Basalt	1	1	A	br.	plagioclase porphyry		
Sandstone	1	5	SA	lt. gy.	fine-grained quartz and andesine cemented by calcite		
Phosphorite	7	1.5	A-SA	dk. br.	glauconite, mineral grains, Foraminifera	Miocene?	m. Miocene (Foraminifera)
109. *FPS 274—Lat. 32°34.9′, Long. 118°48.3′; 2550 feet; dredge; Saddle southeast of Tanner Bank*							
Basalt	1	4	SA	br.	olivine altered		
Phosphorite	5	3	SR	lt. br.	4 pieces have vein of barite	Miocene?	

110. *Scr. 0039—Lat. 33°02.5′, Long. 119°41.2′; 2862 feet; snapper?; Ten miles southwest of San Nicolas Id.; transported*

Volcanic Rock (?)	1	1	SR	gn.	very highly altered to chlorite (?)		
Mudstone	1	0.5	SA	yel.	probably phase of phosphorite		l.u. Miocene (Foraminifera)
Phosphorite	3	2	A-R	br.	irregular layers	Miocene?	

111. *Scr. 9667—Lat. 33°14.2′, Long. 119°20.5′; 210 feet; snapper; Shelf east of San Nicolas Id.; transported*

Andesite?	1	0.5	R	gy.			
Sandstone	10	0.2	A	br.	quartz, plagioclase cemented by calcite		
Limestone	10	0.4	A	br.	porous		

112. *FPS 150—Lat. 33°17.0′, Long. 119°30.4′; 66 feet; dredge; Shelf north of San Nicolas Id.; outcrop*

Sandstone	9	10	A	yel. gy.	calcite cement	Eocene	
Limestone	40	5	A	gy.	homogeneous, shaly	Eocene	

113. *Scr. 6459—Lat. 33°40.5′, Long. 119°47.3′; 1452 feet; corer; Slope south of Santa Cruz Id.*

Phosphorite	2	4	A-SA	dk. br.-lt. gy.	some contain oölites and glauconite, but most are homogeneous		

114. *FPS 318—Lat. 33°56′, Long. 119°51′; 288 feet; small dredge; small hill southwest of Santa Cruz Canyon; outcrop*

Breccia, volcanic	1	1	A	br.-bk.	includes basalt(?) fragments; freshly broken		

115. *Pio. 7—Lat. 31°45′, Long. 119°12′; 3082? feet; snapper; Ridge west of Long Basin*

Manganese oxide	11	2	A	br.	probably all are parts of single slab		

116. *Pio. 751—Lat. 31°56′, Long. 119°25′; 4254? feet; snapper; Ridge west of Long Basin: probably near outcrop*

Limestone	30	0.5	SA	yel.	silty, uniform		

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
117. *FPS 189—Lat. 32°20′, Long. 119°40′; 1380 feet; small dredge; Northeast Bank; transported*							
Basalt	20	0.3	A-SA	br.	plagioclase porphyry		
Phosphorite	1		A		Foraminifera; spicules, glauconite		
118. *FPS 187—Lat. 32°23′, Long. 119°37′; 1698 feet; snapper; Northeast Bank; transported*							
Basalt	5	0.9	SR-R	bk., red	massive to scoriaceous		
Sandstone	7	0.8		yel.-dk. gy.	round to subround grains of basalt cemented by phosphorite		
119. *Pio. 17—Lat. 32°31.5′, Long. 119°28.8′; 1854 feet; snapper; Ridge northeast of Northeast Bank*							
Phosphorite	2	4	A	br.	layers; oölites; Foraminifera	Miocene?	
120. *Pio. 29—Lat. 32°42.0′, Long. 119°51.5′; 2316 feet; snapper; Elevation 20 miles northwest of Northeast Bank*							
Basalt-andesite	1	4	A	br.	plagioclase porphyry		
121. *FPS 183—Lat. 32°48.5′, Long. 120°18.0′; 2880 feet; dredge; Top of continental slope; near phosphorite and andesite outcrops*							
Granite	1	5	R		biotite; coarse-grained		
Andesite	200	15	S-R	yel.	plagioclase porphyry		
Sandstone	2	10	A	br.-gy.	weathered; calcite cement		
Limestone	1	8	A	br.	opal on joint surface	Miocene	
Chert	1	4	SR	gn.-red	banded	Franciscan (Jur.?)	
Phosphorite	100	18	A	br.	oölitic to homogeneous	Miocene?	m. or u. Mio. (Foraminifera)

Sandstone	69	20	A-SA	lt. gn.	quartz, rock fragments; hydrothermal alterations	Franciscan (Jur.?)	
Limestone	1	13	SA	br.	finely crystalline	Miocene	
Phosphorite	2	4	A-SA	br.-bk.	shaly		l.u. Miocene (Foraminifera)
123. *FPS 158—Lat. 32°56.5′, Long. 120°05.8′; 1260 feet; dredge; Ridge west of Tanner Basin; limestone and phosphorite outcrop*							
Sandstone	1	3	A	reddish	plagioclase grains; calcite cement		
Limestone	16	45	A	white-br.	massive; crystalline; 3 have cover of phosphorite		
Limestone	1	7	SR	br.	mostly oölitic; cherty	Miocene	
Limestone	2	15	SR	white	coral; pelecypods; gastropods; Bryozoa; algae		
Phosphorite	9	35	SR	br.	gabbro cobbles enclosed	Miocene?	l. Mio. to Quat. (Foram.)
124. *FPS 159—Lat. 33°03.6′, Long. 120°10.0′; 1620 feet; dredge; Ridge west of Tanner Basin; phosphorite outcrop*							
Granite	1	7	A	gn.	medium-grained; slightly altered; possible segregation phase		
Limestone	1	6	A	br.	crystalline		
Chert	2	8	SA	gn.	irregular layers	Franciscan (Jur.?)	
Phosphorite	40	30	SA	lt.-dk. br.	many layers; oölites; glauconite; cobbles of sandstone, gabbro, schist	Miocene?	Miocene (Foraminifera)
125. *FPS 160—Lat. 33°09.0′, Long. 120°11.6′; 1170 feet; dredge; Ridge west of Tanner Basin; sandstone outcrop*							
Basalt-andesite	28	6	A	br.-dk. gy.	fine-grained; scoriaceous		
Basalt-andesite breccia	8	6	A	dk. gy.	large irregular scoriaceous fragments included; some flow structure		
Andesite	1	6	R	br.	plagioclase porphyry; weathered		

APPENDIX—*Continued*

Rock type	Number pieces	Max. diam. (cm)	Shape	Color	Notes	Lithologic affinities	Age of enclosed fossils
125. *FPS 160—Lat. 33°09.0′, Long. 120°11.6′; 1170 feet; dredge; Ridge west of Tanner Basin; sandstone outcrop—Continued*							
Sandstone	300	18	A	br.	chlorite cement	Franciscan (Jur.?)	
Limestone	1	4	A	br.	finely crystalline		
Chert	4	5	A	gn.	cracked	Franciscan (Jur.?)	
Phosphorite	4	4	SA	br.	some homogeneous; rest contains glauconite, coprolites	Miocene?	
126. *FPS 162—Lat. 33°08.0′, Long. 120°21.8′; 780 feet; dredge; Ridge west of Tanner Basin; phosphorite outcrop*							
Limestone	1	9	A	dk. gy.	cherty; secondary calcite in joints	Miocene	
Phosphorite	6	60	SA	br.	contains cobbles of limestone, dacite, and andesite or basalt	Miocene?	nodules, m. or l. Mio.; matrix: u. Plio. or Quat. (Foraminifera)
127. *FPS 164—Lat. 33°06.2′, Long. 120°34.4′; 6900–8880 feet; dredge; Continental slope; transported*							
Basalt	17	3	A	dk. bu.	plagioclase porphyry		
Phosphorite	6	0.3	SR	br.			
128. *FPS 166—Lat. 33°01.7′, Long. 120°36.0′; 10320 feet; corer; Bottom of continental slope; transported*							
Basalt	1	0.8	SA	dk. br.	plagioclase porphyry; glassy groundmass		
129. *FPS 176—Lat. 33°06.1′, Long. 120°58.4′; 2850–3120 feet; dredge; San Juan Seamount; outcrop*							
Basalt	20	3	A	br.	plagioclase porphyry; glassy groundmass (palagonite?); fresh fractures		

Basalt.....	2	0.3	A	br.	plagioclase porphyry; 1 has opal vein; weathered (palagonite?)		

131. *FPS 180—Lat. 33°04.7′, Long. 120°56.0′; 4500–5400 feet; small dredge; San Juan Seamount; outcrop*

Basalt.....	100	3	A	dk. gy.	plagioclase porphyry; some scoriaceous; weathered (palagonite?)		

Contribution No. 254

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A SIMPLE DEVICE FOR THE ADDITION OR REMOVAL OF SOLUTIONS OR GASES TO A CLOSED SYSTEM

THE aseptic removal of samples of gas or media from a closed bacteriological system has been simply and effectively accomplished using sleeve-type, soft rubber stoppers, such as those used to cover serum bottles. This device, described below, also provides for the aseptic introduction of nutrients, buffers or other materials without opening the system or otherwise interrupting the experiment.

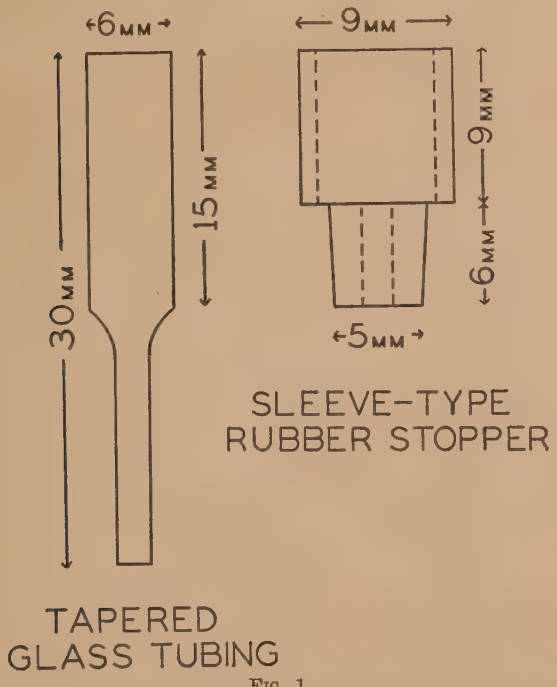

FIG. 1

A sleeve-type, soft rubber stopper measuring 5 mm at the base (see diagram) is inserted in a glass tubing of 5 mm inside diameter or slightly smaller. This tubing

is pressed into a hole in the rubber stopper or closure for the bacteriological system. It is usually advisable to taper the tube for a better fit (see diagram). The media or gas may be removed by inserting a hypodermic needle (20 gauge, 1½ inch length), attached to a syringe or sampling device, through the sleeve-type rubber stopper. Several precautions are necessary. The stopper itself should be selected with care to insure sufficient thickness to the top wall so as to cut the exchange of gases to a minimum and in order to provide for adequate re-sealing if frequent punctures are necessary. The glass tube and sleeve-type stopper should be fitted with care to avoid leakage at this joint. The glass tubing should be cut off flush with the bottom of the closure stopper since complete removal of all gas bubbles would become impossible.

The author has found such a sampling device of indispensable value in the study of gas-producing organisms of certain marine bottom deposits. The gases formed in the culture system are collected directly in the Orsat gas analyzer with a hypodermic needle attached by a short rubber tubing to the inlet stopcock of the apparatus. Hydrogen-ion concentration or oxidation-reduction intensity changes can be followed at any desired interval by use of a sterile Luer-type syringe and hypodermic needle for the withdrawal of suitable aliquots. In a similar manner, samples are collected for other chemical analyses, for population estimations or for the transfer of cultures.

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Contribution No. 255

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DEVELOPMENT OF THE REPRODUCTIVE SYSTEM AND VARIATIONS IN SEXUALITY IN PECTEN AND OTHER PELECYPOD MOLLUSKS

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The species of the genus *Pecten* are of much interest biologically, not only because of their adaptations for a peculiar mode of locomotion but also because of their variations in sexuality. Most of the species are more or less regularly hermaphroditic but with many variations in the relative proportions and sequence of maturity of the two types of sexual cells.

In three of these species the writer has had the opportunity of examining large numbers of individuals of all ages and has studied the development of the reproductive system and the changes in functional sexuality experienced by some of these individuals during their lifetimes. One of these species, *P. irradians*, has been studied previously, particularly by Belding (1910) and Gutsell (1931), while Drew (1906), Fullarton (1890), Dakin (1909) and Dalmon (1938) have reported on the sexuality of various others. A comparison of the sexual conditions found in this genus with those of other pelecypods may contribute to a more comprehensive understanding of the general problem of sexuality in animals.

It is customary to think of the two sexes as representing two contrasted and mutually exclusive aspects of physiology. In reality however such is not always the case, since it is well known that in certain animals and plants there are the same intergradations in sexuality as there are in other characteristics of the individual. Furthermore there are many invertebrates and some plants, as well as a few fishes, which change their sexuality during their lifetimes, functioning either as male or as female when young and later changing to the opposite sexual phase. In some species this occurs not merely once but several times.

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In some of these organisms the sex can be controlled experimentally by varying the nutrition or changing the chemical or physical conditions of the environment, as is the case also with many of the other characteristics of the animal or the plant. The inherent sexual tendencies may be so evenly balanced that relatively slight alterations of the environmental conditions are sufficient to divert the process of sexual differentiation toward the one sexual phase or the other. Once initiated the process may lead either to a complete transformation of functional sexuality or, more often, to an intermediate condition with a combination of the characteristics of both sexual phases. Such environmental effects however are possible only in species which have an inherent tendency toward an ambisexual, or hermaphroditic, condition.

All these aspects of sexuality are found in various species of bivalve mollusks. Except in those that are strictly of separate sexes the gonads contain the antecedent cells of both eggs and sperm. As a general rule the male cells mature in advance of the female cells, whereby the initial phase of functional sexuality is male. Such individuals are said to be protandric. Less frequently the initial phase is female and the individual is proterogynic. In functional hermaphrodites the eggs and sperm develop concurrently. Among the individuals of a single species some may be protandric, some proterogynic, others unisexual and still others functionally hermaphroditic. Consequently the sexuality of a species can be determined only by the examination of many individuals at all periods of life.

The change from one sexual phase to another, when it occurs, is usually, although not invariably, gradual with intervening stages in which the gonad presents all grades of ambisexuality. Such individuals, if protandric, might erroneously be thought to be males if examined when young and females if older, while they would be classed as hermaphrodites if found only in the stage of sexual transformation. They may represent, on the contrary, merely the successive phases experienced by each normal individual during its lifetime. In some species definite proof of these changes in sexual phase can be obtained by isolating the individual or by marking the shell and observing the sexuality at successive spawning periods. In others it is necessary to infer the changes by examining the gonads of many different individuals of known ages.

It is customary to classify all these aspects of sexuality into two

ain groups, namely, *A*, ambisexuality (monoecism, herma-
roditism) and *B*, unisexuality (dioecism, gonochorism). These
vo groups are not mutually exclusive however, because certain
ominantly unisexual species may have local races or environmental
odifications which are hermaphroditic. Furthermore accidental
r developmental hermaphroditism is of occasional occurrence in
ost of the unisexual species and unisexual individuals are some-
mes found in dominantly hermaphroditic species.

Types of Ambisexuality

In the pelecypods, as in some other groups of animals and plants,
ere are various manifestations of ambisexuality. These include
a) functional hermaphroditism, in which both types of gametes
come mature at the same time; (*b*) consecutive sexuality, in
hich the individual functions in one sexual phase when young and
ter changes to the opposite sexual phase; (*c*) rhythmical con-
cutive sexuality, in which there is a repetition of alternating male
id female phases; and (*d*) alternative sexuality, in which it is
mpossible to predict from one sexual phase what the nature of the
llowing sexual phase will be. In some species a single sexual
ase may extend through an entire annual reproductive season,
hile in others it may be of only brief duration.

Hermaphroditism in Normally Unisexual Species

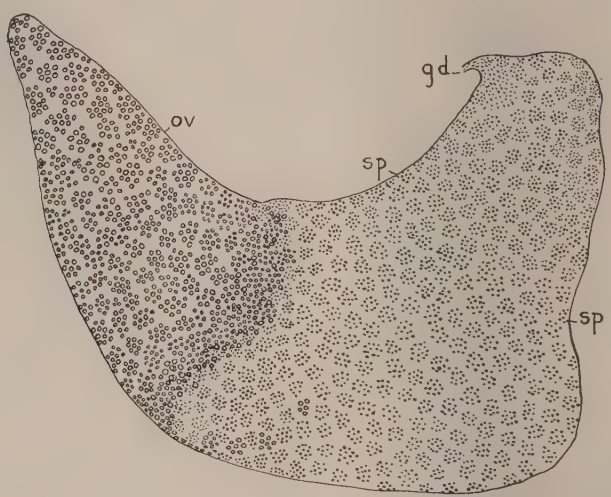
Less than 400 of the 10,000 or more described species of pelecy-
ds are known to be normally hermaphroditic. But in most of
e typically unisexual species which have been studied extensively
small percentage of hermaphroditic individuals has been found.
hese are generally considered to be the result of an accidental or
normal mode of embryonic development, due to the failure of
e hereditary sex-differentiating mechanism to function normally.
hey also prove that the primary germ cells have an ambisexual
tency. The genetic constitution of different individuals must
rmally be such as to divert the sexual differentiation in the direc-
n of maleness or of femaleness by inhibiting one of the alter-
tive potencies of the cells or by stimulating the other. If such
tion fails to occur or if it is incomplete, varying degrees of
rmaphroditism will result. Environmental influences may some-
nes be responsible.

Whatever may be the cause there is good evidence that this type

of hermaphroditism is more common in some species than i others. For a particular species the incidence also appears to var with the locality, indicating the occurrence of different local race (Coe, 1938). The extent of ambisexuality of this type may var from a few gametes of the opposite sexual phase to complet bilateral hermaphroditism. Such variability in the expression o sexuality is particularly characteristic of the genus "*Anodont* (Bloomer, 1939; van der Schalie, 1941).

Variations in Sexuality in Species of Pecten

Among the many species of the genus *Pecten* are some whic illustrate nearly all the aspects of sexuality that have been mer

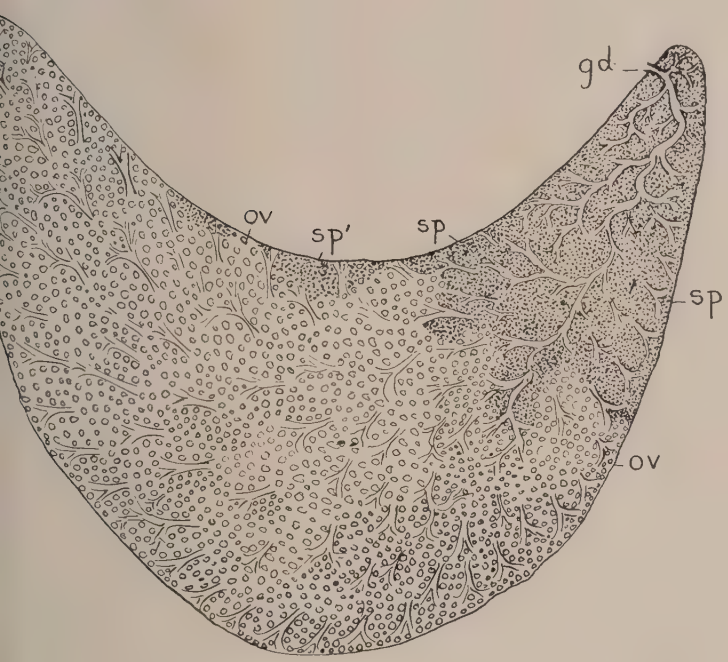


Textfigure 1. Protandric phase of gonad of *Pecten latiauritus*, showin the relatively large mass of spermatic tissue (*sp*) as compared with ovaria tissue (*ov*) preceding the first discharge of sperm; *gd*, genital duct.

tioned. Most of them are more or less regularly functionall hermaphroditic but with many individual variations in the expre sion of sexuality. Protandry is of common occurrence. At lea one species, *P. magellanicus* (*tenuicostatus*) is unisexual.

In the hermaphroditic species the proximal end of each of th paired gonads is differentiated into a spermary, while the dist portion functions as an ovary (Textfigure 1). In most individua

e two portions are sharply demarcated but in some the separation incomplete, with small masses of spermatic tissue among the arian follicles or some ovarian follicles in the spermatic portion the gonad (Textfigures 1, 2).



TEXTFIGURE 2. Gonad of *Pecten latiauritus* in late sexual maturity, show- the proximal end differentiated as a spermary (*sp*) and the distal portion an ovary (*ov*); *gd*, genital duct. Small patches of spermatic tissue (*sp'*) scattered on the dorsal side of the ovarian portion of the gonad. The atively small amount of spermatic tissue and ripe spermatozoa indicate t a considerable proportion of the sperm has been already discharged.

This irregularity in the distribution of spermatic and ovarian sues may occasionally lead to the formation of gonads which are nost exclusively of one sexual type, either male or female. With- t careful examination such individuals would be considered as isexual. Such extreme restrictions of one of the two types of xual cells have been previously reported by Gutsell (1931) for

P. irradians. The fact that the ovarian tissues become pink or re when mature or partially mature, while the spermatic tissues ar white or cream colored, facilitates the identification of the variou grades of ambisexuality.

Not only is there considerable variability in the proportion o male and female tissues in the gonad but the periods of maturit and of spawning of the two types of gametes varies in differen individuals. In general there is a strong tendency toward pro tandry and some or all of the sperm is discharged before the egg are fully ripe. In the young gonad spermatogenesis may be i progress long before the ova have begun the deposition of yolk

Examination of sexually mature individuals of several specie indicates that each individual usually experiences several spawn ings of each type of gamete during the prolonged reproductive sea son. Under experimental conditions it is more common to elic the discharge of sperm in functionally hermaphroditic individual than it is to induce egg spawning. Less frequently both types o gametes are discharged simultaneously.

From these experiments, as well as from examination of th gonads, it is inferred that as a general rule much of the sper is emitted some days previous to the first of the several periods o egg-spawning. The remaining sperm, as well as that which i formed later, is presumably discharged between the ovulatio periods, rendering self-fertilization in nature unusual. Exper mentally, however, self-fertilization in fully ripe functional he maphrodites seems to take place as readily as cross fertilizatio Both Belding (1910) and Gutsell (1931) obtained self-fertilizatio and apparently normal embryological development in *P. irradians*

Embryonic Development of the Gonads

The gonads in the pelecypods consist of a pair of profuse branched tubules with each of the terminal branches expande into a follicle in which the gametes are formed. As a gener rule the gonads are limited to the mesosoma, or visceral mass, b in the mussels they extend also into the mantle lining the valves o the shell and in *Anomia* into the mantle on the right side of th body. Each of the two gonads usually has a single efferent du and this may open directly into the mantle cavity or, as in *Pecte* into the renal organ and thence to the mantle cavity and exterio

The two members of the pair of efferent ducts are frequently united by a cross branch near their openings (Coe and Turner, 1938).

In some of the hermaphroditic species both ova and spermatozoa may be formed in the same follicles and in other species in separate follicles. In some of these the ovarian and spermatic follicles are situated in close proximity on the same tubules, while in others, as *Pecten*, they are segregated in different portions of the gonad or in separate organs (*Musculium*), but have a common efferent duct. Finally there are at least two genera (*Poromya* and *Silenia*) in which the male and female portions are completely separated, with separate efferent ducts.

The embryonic development of the gonads has been studied by the writer in *P. circularis*, *P. irradians* and *P. latiauritus*. In each of these the gonads are formed by the interlacing of the tubules of a pair of racemose glands, with right and left genital ducts leading to the renal organs and thence to the openings of the latter into the mantle cavity and the exterior. The gland and duct on the right side of the body are much larger than those on the left. Both the spermatozoa and the ova pass through the same ducts.

The primordia of the developing gonads in the young *Pecten* consist of two groups of primary germ cells and follicle cells, situated near the later opening of the genital ducts. They each develop into profusely branching tubules which penetrate the connective tissue of the visceral mass, much as described by Coe and Turner (1938) for the clam *Mya*. As each of the branching tubules extends further into the visceral mass it carries with it derivatives of the primordial germ cells as primary gonia. The earliest gonia to begin proliferating into sexual cells are those which are situated in the proximal portions of the branching tubules, nearest the openings of the genital ducts.

As the gonia proliferate they enlarge the ends of the branches into rounded follicles, in which gametogenesis is completed. These earliest, or proximal, follicles become differentiated into the spermatic portion of the gonad, while those which form later, as the primary tubules extend farther into the visceral mass, form the ovarian portion. A tendency toward protandry thus becomes evident at an early stage of development, in as much as the spermary is differentiated first and the ovary later. This condition is in some respects similar to the type of consecutive sexuality

characteristic of the ovoviviparous oysters and wood-boring mollusks, discussed in a later section of this report, in which there are distinct primary (male) and secondary (female) sexual phases.

It is possible however that this explanation is illusory and that the fundamental principle in the differentiation of spermary and ovary is actually a difference in polarity. The proximal end of each tubule may lie in a polarized field which differs from that of the distal end. Such an explanation seems to apply to many similar examples of embryonic induction. An anterior-posterior differentiation, or polarity, is characteristic of the gonads of many other ambisexual animals. In some of these the spermatic portion is anterior and in others posterior. In the pelecypods it is usually anterior or dorsal.

Sexuality of *Pecten latiauritus* Conrad

This may be considered a typical example of ambisexuality. Individuals of this species are commonly found attached to marine plants and other objects along the open California coast. They sometimes appear on the piles of the pier at the Scripps Institution of Oceanography in vast numbers. Both sexually mature individuals and young may be found in this locality at all seasons of the year, although the principal spawning periods occur in early spring and early autumn. Young individuals become sexually mature at the age of about four months.

Examination of the gonads of several hundred individuals has revealed much variation in the proportion of spermatic and ovarian tissues and in their distribution within the gonad. In the youngest individuals the spermatic portion is usually several times as large as the ovarian part and the spermatozoa are usually ripe before the ova are fully mature (Textfigure 1). Following the discharge of most of the ripe sperm, the ova increase rapidly in size and the ovarian tissues occupy the larger part of the gonad (Textfigure 2). A considerable proportion but not all of the ova are discharged at the first ovulation. The spermatic tissues then increase in size. Successive alternating periods of sperm discharge and ovulation evidently follow but the extent of each has not been determined. Eventually nearly all the ripe gametes of both sexual types will have been discharged and the shrunken, flabby gonad loses its red and yellowish white contrasted coloring

and becomes dull grayish brown. Such ova and spermatozoa as are not discharged are absorbed by phagocytosis and the gonad returns to a resting condition. Residual gonia preparatory to a second sequence of stages in gamete production always remain on the walls of the follicles but the evidence indicates that relatively few individuals survive long enough for the full completion of a second spawning season.

Different individuals show much variation in the relative extent of spermatic and ovarian tissues even when young and a few individuals have been found which closely approach a unisexual condition, the entire gonads consisting almost exclusively of tissues of either the male or female sexual type, as has already been mentioned for *P. irradians*.

In fully ripe individuals spawning may sometimes be induced by the presence of sperm in the water and sometimes by changes of temperature.

Sexuality of *Pecten circularis aequisulcatus* Carpenter

In this species, which is common in protected bays on the coast of California and southward, the variations in sexual phases are similar in most respects to those of the preceding species. In San Diego and Mission bays spawning may occur in any month of the year but is more frequent in spring and early summer. Most individuals have completed the season's spawning before the end of July.

Young individuals have a strong tendency to protandry and this is also characteristic of older individuals at the beginning of the second spawning period. In this species, as in others of the genus, the mature ova are provided with a red pigment. Consequently the ovarian portion of the gonads changes from pale yellow to pink and then to red as the ova gradually increase in size and maturity. The spermatic portion is yellowish white. After the completion of spawning the gonad becomes pale yellowish brown, as the unspawned ova are gradually absorbed by phagocytosis. Residual gonia provide for a second and sometimes a third spawning season.

Because of the extended spawning season there is much variation in the sexual condition of different individuals collected at the same time. Some may have both ovarian and spermatic portions

of the gonad distended with apparently ripe gametes, others appear to be functional either as male or as female, while still others are in the early stages of gametogenesis. Not infrequently the spermatic portion of the gonad is distended with ripe spermatozoa before the ova have begun the deposition of yolk or between two successive periods of ovulation. There can be no doubt that alternation of functional sexual phase is usual in this species and that in consequence the simultaneous spawning of the two types of gametes is unusual. Self-fertilization is thus rendered improbable in nature although it can be induced under experimental conditions. If ripe ova are forced through the genital ducts by pressure at a time when the same individual has retained some mature spermatozoa apparently normal embryos may result.

In this species also the gonads show much variation in the relative extent of spermatic and ovarian tissues. This results not only because of the tendency to alternation of sexual phase but also because in a very small percentage of individuals either one or the other of the two types of tissue is very much reduced even at an early age. Here again there is occasionally an approach to unisexuality. There seems to be no way by which it can be determined whether this variation in sex expression is the result of differences in genetic constitution or whether it is due to accidental or environmental causes during development.

Serial sections of the gonad show a zone between the spermatic and ovarian portions of the gonad in which there is considerable overlapping of male and female tissues. A few of the spermatic follicles may extend as islands far into the dorsal side of the ovarian region, while ovarian follicles may encroach on the ventral area of the spermatic tissues and follow the genital ducts into the interior. Ambisexual follicles, however, rarely occur.

Sexuality of *Pecten irradians* Lamarck

The sexuality of this species, which is common in protected bays along the Atlantic and Gulf coasts of the United States, has been investigated by Belding (1910), Gutsell (1931) and others. The male and female portions of the gonads are similar to those mentioned for *P. circularis* and *P. latiauritus* and the observations of both Belding and Gutsell indicate that the eggs and sperm are usually discharged at separate times. Both investigators, however,

were able to obtain self-fertilization under artificial conditions. Observations by the present writer during several seasons at Woods Hole, Massachusetts, indicate that protandry is usual, although incomplete and not invariable.

Sexuality of other Species of *Pecten*

In the European species *P. opercularis* and *P. maximus*, both of which are hermaphroditic, Fullarton (1890) and Dakin (1909) report that some individuals are distinctly protandric at each spawning season, nearly all of the sperm being discharged before the eggs of the same individual become fully mature. Other individuals appear to be proterogynous. In both of these species there is a brief period when the individual is morphologically hermaphroditic but functionally male and another period when it is functionally female, with an intervening stage when it may be functionally as well as morphologically hermaphroditic. Dalmon (1938) however concluded that both these species are so distinctly protandric as to render self-fertilization impossible. *P. (Chlamys) varia*, on the contrary, exhibits all grades of hermaphroditism but with a strong protandric tendency. Both spermatozoa and ova are formed in the same follicles. During the transition from male to female phase both types of nearly mature gametes may sometimes be found together in the follicle; therefore the possibility of self-fertilization cannot be excluded theoretically. It is uncertain whether these differences have a genetic basis or whether they are determined by environmental conditions.

Other species of the genus which have been reported as being normally hermaphroditic include *P. islandicus, asper, flexuosus, glaber, jacobaeus, nux* and *pyxidatus* (Pelseneer, 1935).

In *P. magellanicus* (*Gmelin*) (= *P. tenuicostatus* Drew) the sexes are separate. When the sexual products are mature the males and females can be easily distinguished by the color of the gonads, the ovaries being pink and the spermaries yellowish white (Drew, 1906). In this, as in other species of the genus, the genital ducts open into the renal organs and thence to the exterior. As is generally the case with pelecypods it seems necessary that the eggs pass through the genital ducts in order to develop normally. Consequently eggs cut from the ovary usually fail to respond to the stimulus of fertilization. The presence of sperm in the water is

sometimes effective in initiating the spawning stimulus in both sexes.

Sexuality of other Pelecypods

Unisexuality

A large majority of the pelecypods in which the sexual conditions have been studied are strictly of separate sexes with the exception of occasional hermaphrodites. A few species, however, as will be mentioned for *Venus* and the oviparous oysters, may experience an ambisexual juvenile phase, while the adults are unisexual. In some populations there appear to be more females than males, due, presumably to the somewhat longer average life of the former. Young individuals are therefore more likely to show equality in the sex ratios. In the oviparous oysters, in which the sexual phase of some individuals changes from year to year, the oldest members of the population are more often in the female phase. This is obviously true in all cases of protandry. In some species the growth rate is faster in young females than in males of the same age. Consequently selection of the largest individuals in a population may give a considerable excess of females (Coe, 1938).

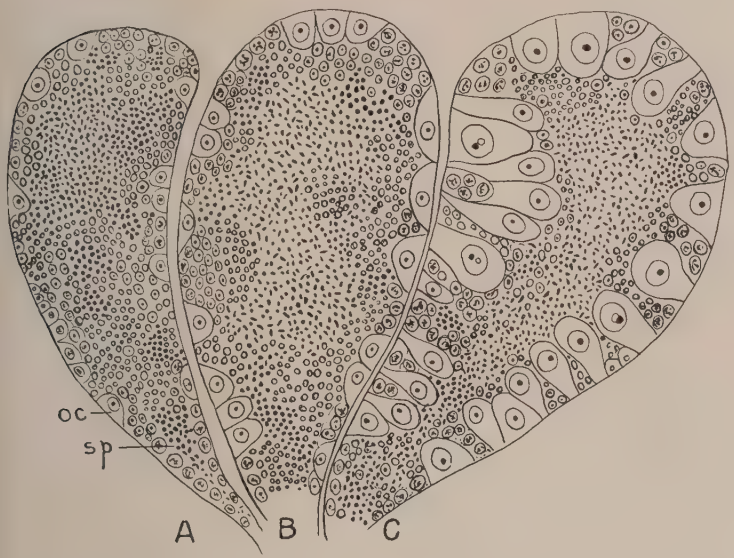
Functional Hermaphroditism

This type of sexuality is found in nearly all phyla of invertebrates and plants. There is here no incompatibility between the male and female sex organs and both types of sexual cells may be produced at the same time although they are not usually discharged simultaneously. Not infrequently, however, this condition is preceded by a brief period of maleness or occasionally of femaleness. In some of these species the extent of protandry is increased by unfavorable conditions and can be controlled experimentally.

In some of the hermaphroditic pelecypods, including the ovoviviparous oysters (*Ostrea*), the wood-boring bivalves (*Teredo*, *Bankia*) and others, each of the gonadal follicles produces both male and female gametes (Textfigure 3). In such cases the gonia which retain their position on the wall of the follicle become transformed into ova, while those in the lumen form spermatozoa.

Most of the ambisexual pelecypods differ from the preceding in that each follicle produces either ova or spermatozoa, but not both. In *Cardium corbis*, of the Pacific coast, eggs and sperm are produced in adjacent follicles (Edmondson, 1920). This is also the

case with *C. crassum* and *C. serratum* of Europe, although *C. edule* is unisexual. In *Tivela stultorum* of the Pacific coast the spermatic and ovarian follicles are also situated in close proximity along the gonadal tubules but as a general rule the sperm and eggs do not mature at the same time (Weymouth, 1923). These individuals are reported to have come from Oceano, California, but the local



Textfigure 3. Development of functional hermaphroditism in *Teredo diegensis*. *A*, immature protandric follicle composed mainly of spermatogenic cells (*sp*) but with small ovocytes on the wall of the follicle; *B*, later stage with many ripe spermatozoa and larger ovocytes; *C*, fully mature phase with continuing spermatogenesis and mature ovocytes.

race of the same species which lives in the San Diego area is almost invariably unisexual. In *Carunculina parva* a few ambisexual follicles were found in four of the five individuals examined by Tepe (1943).

As regards their sexual conditions therefore these hermaphroditic pelecypods form a graded series from those in which each follicle is usually ambisexual as in *Teredo diegensis* (Textfigure 3), to those having follicles of an exclusively male or female nature.

These two types of follicles may be interspersed or, as in *Sphaerium* (Monk, 1928) and in most species of *Pecten*, segregated into separate portions of the gonad.

Consecutive Sexuality

This type of sexuality implies a change in the functional sexual condition of the individual, or sex reversal. The male and female phases may intergrade with an intermediate period of ambisexuality, or they may be sharply separated. Consecutive sexuality is of wide occurrence, being found not only in most classes of mollusks but in other phyla or invertebrates, including annelids, echinoderms, nemerteans and crustaceans, as well as in some plants and a few fishes. Most of the invertebrates of this type experience but a single change of sex, usually from male to female. An overlapping of the two sexual phases may produce a brief period of hermaphroditism, at which time self-fertilization may be possible.

The histological basis of this type of sexuality depends upon the presence of an essentially ambisexual gonad, associated with a hereditary mechanism which causes the activation of one of the two types of sexual cells in advance of the other.

Consecutive sexuality may become manifest during a single spawning season, one sexual phase following the other without an intervening period of recuperation, or there may be a more or less prolonged period of sexual inactivity between two successive phases. When there is but a single spawning period each year there is often a period of several months between the termination of one sexual phase and the beginning of the next.

In *Venus mercenaria*, as determined by Loosanoff (1937), nearly all individuals experience a juvenile functional male phase when only a few months of age and only a small fraction of the definitive size. Following this initial male phase the sexes are with few exceptions strictly either male or female, with approximately equal numbers of each sex. There is no indication of a further change of sexuality. The primary, juvenile, gonads are invariably more or less distinctly ambisexual, forming a graded series from predominantly male to predominantly female, although about 98 per cent of all individuals are protandric. The remaining 2 per cent are proterogynic. The adults are thus dioecious, following (with few exceptions) a more or less aborted primary male phase.

The sexual conditions in different individuals of this species may be schematized as follows:

1. Juvenile true male phase (exceptional) . . . Adult male (true male).
2. Juvenile ambisexual male phase . . . Adult male.
3. Juvenile ambisexual male phase . . . Adult female (protandric female).
4. Juvenile ambisexual male phase . . . Adult hermaphrodite (exceptional).
5. Juvenile female phase (exceptional) . . . Adult female.

Another example of consecutive sexuality is found in the wood-boring mollusk *Bankia setacea*, although the protandric females may experience a second change of sexual phase if the length of life of the individual is sufficiently prolonged. Self-fertilization is sometimes possible in the juvenile phase of protandric females, due to the overlapping of male and female phases (Coe, 1941). The population contains a small proportion of true males as well as of juvenile females; in the latter the initial male phase is aborted or omitted.

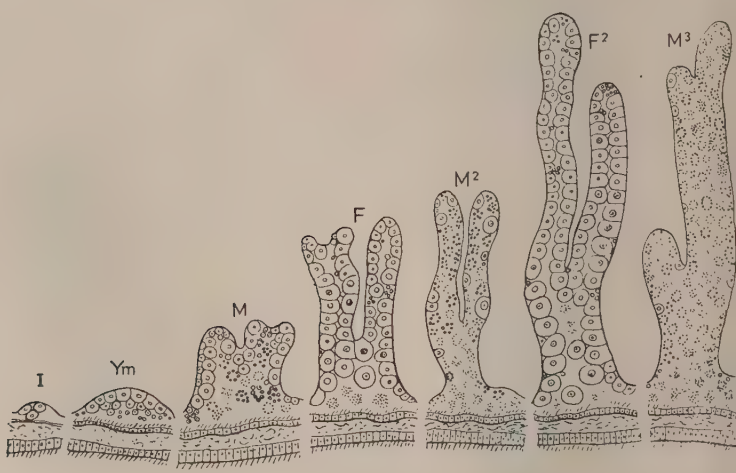
Consecutive sexuality is also characteristic of *Xylophaga dorsalis*, another species of wood-boring pelecypod, most of the smaller and younger individuals functioning as males and the larger as females (Pynchon, 1941). The change of sex is indicated not only by the gonad but also by the seminal vesicles, which are large in the male phase but diminish in size and eventually disappear in the female phase. This is one of the few pelecypods in which a specialized storage organ for the sperm has been found but there is no direct evidence that self-fertilization occurs.

Rhythmical Consecutive Sexuality

The tendency toward an alternation of male and female phases which is so incompletely manifested by the ambisexual species of *Pecten* reaches full expression in several other groups of pelecypods. In the ovoviviparous oysters, of which *Ostrea lurida* may be taken as an example, the initial phase is usually male, followed by a series of alternating female and male phases throughout life. The eggs are fertilized within the mantle cavity, usually by sperm which have been discharged into the water by other individuals in

the vicinity. The fertilized eggs are carried through the gills to the pallial chamber of the parent, where they complete development to the adult form.

As shown in Textfigures 4, 5, 6, the primary gonad is distinctly ambisexual, with a layer of ovocytes on the walls of each of the follicles and spermatogenic cells in the lumen. The spermatozoa



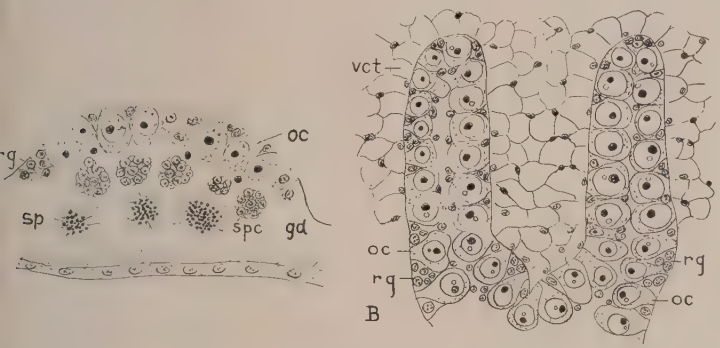
TEXTFIGURE 4. Rhythmical consecutive sexuality in *Ostrea lurida*; sequence of sexual phases. *I*, portion of undifferentiated primordium of gonad; *Ym*, early stage in primary male phase; *M*, hermaphroditic male phase with layer of ovocytes on wall of follicle and spermatogenic cells in the lumen; *F*, transition from male phase to first female phase, with ovocytes filling the follicle and a few remaining balls of spermatozoa in the genital canal (*gc*); M^2, second male phase, with spermatogenic cells filling the follicle; F^2, second female phase; M^3, third male phase.

are formed before any of the ova are mature, indicating that the individual has reached the primary male phase.

Following the discharge of most of the spermatozoa, the ova become mature and are discharged when the individual functions in the first female phase. After the ova are spawned, residual gonia which have been derived originally from the primordial germ cells of the embryo, remain upon the walls of the follicles (Textfigure 5, *B*). These later multiply and some of them become differentiated into the spermatogenic cells of the following, second

male phase. Others remain to be differentiated into the ova of the second female phase. If the individual continues to survive, one or more additional sequences of male and female phases will follow (Textfigures 4, 6).

The time which elapses between the successive sexual phases depends upon the temperature of the water, the season when hatched and other environmental conditions. On the coast of southern



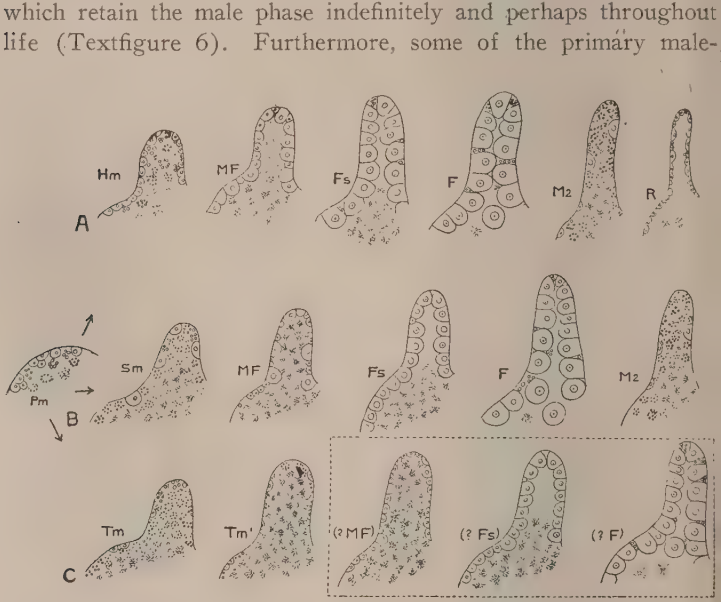
Textfigure 5. Primary and secondary sexual phases of *Ostrea lurida*. *A*, primary ambisexual male-phase condition, with peripheral layer of ovocytes (*oc*) and groups of developing spermatocytes (*spc*) and spermatozoa (*sp*) in the lumen; residual gonia (*rg*) preparatory to the second male phase lie among the ovocytes; *gd*, ciliated genital duct. *B*, portions of two follicles of first female phase surrounded by much vesicular connective tissue (*vct*); residual gonia (*rg*) preparatory to the following male phase lie upon the walls of the follicles, while small follicle cells are scattered in the lumens.

California those individuals which are hatched in early spring may sometimes have three phases of functional sexuality during one calendar year. A brief male phase when the individual is 4 to 6 months of age is followed by a more lengthy female phase. The latter may be concluded in time for a second male phase in the autumn. Spermatogenesis is usually in progress before the larvae of the female phase have left the mantle cavity.

Individuals which are hatched in the summer or early autumn complete only one or two sexual phases in that calendar year. This variation in periodicity provides the population with individuals in both sexual phases at all times during the spawning season (Coe, 1932, 1934). Two separate spawning periods, resulting in two

broods of young, may sometimes occur during a single female phase. A similar series of sexual phases occurs in the European *Ostrea edulis* (Cole, 1942).

In addition to those individuals with regularly alternating sexuality the population contains a small proportion of true males which retain the male phase indefinitely and perhaps throughout life (Textfigure 6). Furthermore, some of the primary male-



TEXTFIGURE 6. *Ostrea lurida.* Sequence of sexual phases in three types of primary male-phase individuals. *A*, hermaphroditic male type (*Hm*); *B*, secondary male type (*Sm*); *C*, true male type (*Tm*); *MF*, functional male phase; *Fs*, transition stage; *F*, functional female phase; M^2, second male phase; *R*, recuperation stage; *Pm*, primary undifferentiated phase. The three phases indicated as possibly following the second true male phase (Tm^1) are of doubtful occurrence.

phase individuals, the so-called ambisexual or hermaphroditic males, have a preponderance of ovocytes in the gonad and change to the female phase after a brief initial male phase. Others of the same age have relatively few and small ovocytes in the primary gonad and retain the male phase much longer (Textfigure 6). And finally, the primary male phase is occasionally aborted or omitted, the first really functional phase thereby becoming female.

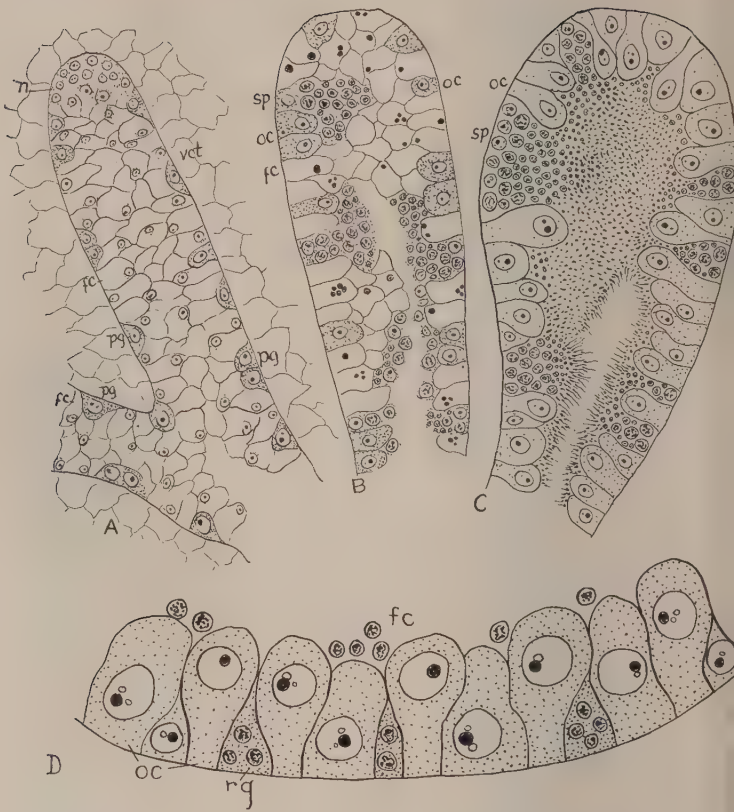
The following scheme will illustrate the successive sexual phases f these different classes of individuals:

1. True male (exceptional) . . . Second male phase . . .
2. Ambisexual male phase . . . First female phase . . . Second ıale phase . . . Second female phase . . . Third male phase, etc.
3. Primary female phase (exceptional) . . . First male phase . Second female phase, etc.

Whether these variations in the expression of sexuality are due different combinations of genetc modifying sex factors or hether they may be influenced by environmental conditions must e determined later by experimental evidence.

Another example of rhythmical consecutive sexuality in pelecy-ods, but with somewhat different modifications, may be taken om the woodboring bivalves. In *Teredo navalis* the variations the sequence of male and female phases are even more pro-ounced than described above for the ovoviviparous oysters. The nbryological development of the profusely branching gonads is milar to that described on the foregoing pages for *Pecten*. In e teredo, however, the primary gonia which are scattered along e walls of the follicles as they branch out into the surrounding nnective tissue are at first without visible sexual differentiation Textfigure 7, *A*). These gonia multiply slowly as the follicles crease in length but no sexual differentiation can be detected until e young teredo has reached a length of about 10 mm. The ermatogonia can be recognized as soon as the primary gonia gin proliferation into groups of nuclei within a cytoplasmic syn-tium. These soon form characteristic spermatocytes, after which ermatogenesis proceeds rapidly. An approximately equal num-r of primary gonia differentiate into ovogonia and their resulting ocytes (Textfigure 7, *B*).

The ovocytes remain attached to the walls of the follicles until lly mature but the spermatogenic cells multiply rapidly and fill e lumens of the follicles (Textfigure 7). In most individuals the ermatozoa become ripe and are discharged before the ova are lly mature. Immediately following this primary male phase the a rapidly increase in size and soon fill the entire follicle. The dividual continues to increase rapidly in size and when it spawns the first female phase it is several times larger than in the male ıase. If the teredo survives sufficiently long a second sequence



TEXTFIGURE 7. Development of primary gonad and consecutive sexuality i *Teredo navalis.* *A*, sexually undifferentiated branching follicle, composed o large vacuolated follicle cells (*fc*) with primary gonia (*pg*) scattered on th periphery; *n*, terminal cap of undifferentiated proliferating nuclei; *vct*, vesicu lar connective tissue. *B*, later stage with differentiated ovocytes (*oc*) an spermatogenic cells (*sp*) derived from the primary gonia; *fc*, remainin follicle cells with disintegrating nuclei and products of abnormal spermato genic cells. *C*, follicle of primary male phase, with spermatogenic cells (*sp* and spermatozoa filling the lumen and large ovocytes (*oc*) on the periphery *D*, portion of follicle in first female phase, with large and smaller ovocyte (*oc*) and with residual gonia (*rg*) preparatory to the following (male phase; *fc*, follicle cells.

f male and female phases may follow but relatively few individ-als live to complete it.

Not all individuals experience tbe same sequence, however, ecause in exceptional cases the ova mature in advance of sper-natogenesis and the first sexual phase is female. At the other xtreme are the so-called true males, in which the ovogonia, if resent, fail to produce ovocytes and such individuals retain the ale phase indefinitely. And finally in a few exceptional individ-als both sperm and ova mature concurrently, giving rise to func-onal hermaphrodites. These five variations in the sequence of xual phases in such individuals as live long enough to experience hat may be considered a complete series may be indicated as llows:

1. True male phase (exceptional) . . . Second male phase . . .
2. Ambisexual male phase . . . First female phase . . . Second ale phase . . . Second female phase (if length of life suffices).
3. Functional hermaphroditic phase (exceptional) . . . Male or male phase . . .
4. Female phase (exceptional) . . . First male phase . . . Second male phase . . .
5. Female phase (exceptional) . . . Second female phase(?)

ortality following the second phase is usually very high and w individuals reach the fourth phase in the localities (Woods ole, Massachusetts and New Haven, Connecticut) where these udies were made.

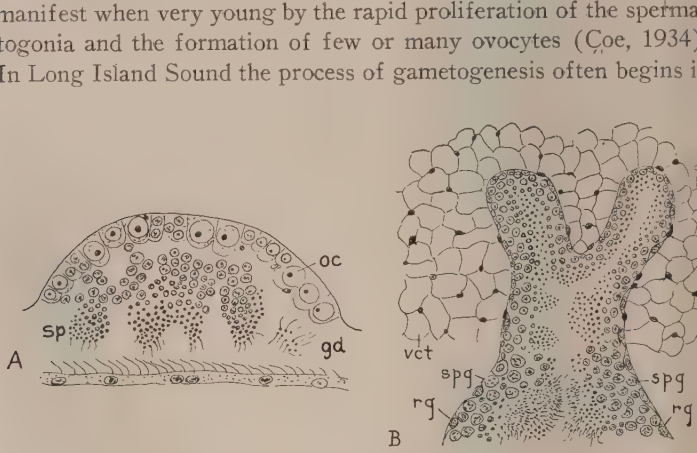
Alternative Sexuality

In the oviparous oysters and perhaps in some other pelecypods e adults function seasonally as separate sexes, although it is ually impossible to predict during one reproductive season the xual phase which the individual will assume at the next (Galtsoff, 38; Needler, 1942).

This type of alternative sexuality is illustrated by the commer-al oyster of the North American Atlantic coast, *Gryphaea virgin-a*. At the first spawning season there is a strong tendency toward otandry, more than 70 per cent of the young oysters in some calities functioning as males at that time (Coe, 1938). After the cond spawning season the number of individuals in each sexual

phase is approximately equal, with a tendency toward an excess o females among the older individuals.

The primary gonad usually contains the antecedent cells of bot sexes (Textfigure 8). Its protandric nature frequently become manifest when very young by the rapid proliferation of the sperma togonia and the formation of few or many ovocytes (Coe, 1934) In Long Island Sound the process of gametogenesis often begins i



Textfigure 8. Primary and secondary sexual phases in *Gryphaea vi ginica*. *A*, juvenile phase in ambisexual condition, with peripheral layer ovocytes (*oc*) and developing spermatozoa (*sp*) in the lumen; *gd*, ciliate genital duct; *B*, follicle of secondary gonad in functional male phase, su rounded by much vesicular connective tissue (*vct*); *spg*, spermatogonia; *r* residual gonia preparatory to the succeeding sexual phase, which may either male or female, of the following year.

the autumn when the animal is only 3 to 4 months of age; it interrupted at the approach of winter and resumed the followin spring. The first spawning occurs at the age of about one yea

The gonads of the young oysters previous to sexual maturit show all gradations between those of the so-alled true males which no ovocytes can be detected and those which develop direct into ovaries. Approximately 1 per cent of these young oyste become functionally hermaphroditic at the first spawning seaso Most of the others function strictly as males or females during th first spawning season, although an occasional individual may pr duce sperm during the early part of the season and ova a fe weeks later (Coe, 1938).

In those young individuals that are to function as males durin their first spawning season, such ovocytes as may be formed in th

early primary gonad are cytolyzed during the progress of spermatogenesis (Textfigure 8).

Female sexual differentiation may be direct with little or no indication of protandry, but it is more often indirect. In the latter case the primary gonad is more or less distinctly ambisexual during the autumn but takes on the appearance of an ovary the following spring by the proliferation of ovogonia and the cytolysis of the spermatogenic cells. A subsequent change from female to male phase evidently results from the later activation of some of the descendants of the primary undifferentiated gonia into spermatogonia. The propagation of such undifferentiated gonia may be continued year after year through a long lifetime, since some residual gonia always remain after spawning (Coe, 1938).

Immediately after each spawning period the residual spermatozoa or ova undergo phagocytosis and cytolysis, leaving only undifferentiated gonia in the collapsed gonadal follicles. The individual thereby returns to a condition similar to that of sexual immaturity. Within a few weeks however the apparently undifferentiated gonia resume activity and then show that they have, in reality become uniformly differentiated into the cells characteristic of the one sexual phase or the other (Loosanoff, 1942). It is not at present known to what extent, if any, environmental conditions determine whether this differentiation shall be in the male or female direction.

The variations in the consecutive sexual phases of this species may be indicated by the following seven series. These are based on the assumption that only those in which the primary gonad is ambisexual experience a change of sex in the second and later years.

1. Primary gonad male . . . Male phase . . . True male . . .
2. Primary gonad ambisexual . . . Male phase . . . Male or female phase . . .
3. Primary gonad ambisexual . . . Functional hermaphrodite (exceptional) . . .
4. Primary gonad ambisexual . . . Male phase (early portion of first year); female phase (later portion of first year) exceptional . . .
5. Primary gonad ambisexual . . . Male phase . . . Female phase . . . Male or female phase . . .
6. Primary gonad ambisexual . . . Female phase . . . Female (or male?) phase . . .

7. Primary gonad female . . . Female phase . . . True female . . .

Some individuals, particularly the so-called true males, are known to retain the same condition of sexuality year after year, while others change their sexual phases repeatedly (Needler, 1942).

Genetical Considerations

In all the foregoing examples of ambisexuality the individual must obviously be determined genetically for both of the alternative phases of sexuality, with associated modifying factors which determine the time of activation of each of the two or more phases. If the primary phase is to be male, as it usually is, such of the primary gonia as have been differentiated into spermatogonia proliferate rapidly, while the ovogonia, if already differentiated as such, remain for a time inactive. This would seem to imply a chemical distinction between spermatogonia and ovogonia, with the subsequent liberation of a specific hormone to which only the spermatogonia are attuned. It is conceivable that a second hormone which activates only the ovogonia is released when a certain physiological condition is reached.

These two hypothetical hormones if released simultaneously may result in functional hermaphroditism, while any one of the three other types of ambisexuality mentioned may depend upon the sequence of the hormones produced and the time which elapses between successive periods of production. In the ambisexual Pectens, activation by the male hormone is soon followed by a similar action of the female hormone and protandry is incomplete or of brief duration. In the oviparous oysters, on the contrary, two successive sexual phases are usually separated by an entire year.

No information is at present available relative to the chromosomal mechanism involved in the determination of sex in the unisexual species but the evidence is in harmony with the view that the prospective sexuality of the individual is dependent upon the quantitative balance of the female- as opposed to the male-determining factors in the hereditary mechanism. This will imply the homozygosity or heterozygosity of the primary sex factors, with their associated modifying factors for the activation or suppression of either the male- or female-determining components at certain stages of development or in harmony with different degrees of physiologi-

cal maturity. These components are doubtless responsive to environmental conditions, although there is no direct proof of truly phenotypic sex determination in the pelecypods. As a general rule in cases of alternative sexuality the male phase is often indicative of immaturity and unfavorable environmental influences, while the female phase is more often associated with optimum physiological conditions. This is consistent with the evidence from other groups of animals and plants.

There are many observations which indicate that the sex ratios of various pelecypods are influenced by environmental conditions but positive experimental proof is still lacking. Among the gastropods, however, such proof has been obtained (Coe, 1943a).

It has been observed repeatedly that there is a larger proportion of females in the yearling population of the Virginia oyster in those years and in those localities most favorable for rapid growth (Coe, 1938). At this age, as mentioned in the preceding section of this report, the functional females are of larger average size than those individuals that are functioning as males. Hence it seems quite possible that temperature and nutritive conditions within the body may influence the proliferation of one rather than the other of the alternative types of sexual cells in the early ambisexual gonad. Such influences are well authenticated among nematodes, annelids, amphibians and plants (Witschi, 1942).

In several groups of animals, both invertebrates and vertebrates, as well as in some plants, there exist local races with differing hereditary types of sexuality. Both unisexual and ambisexual races are reported by Bloomer (1939) in *Anodonta cygnea,* and the evidence for such local races in *Tivela stultorum* has been mentioned on a preceding page. Similar races have been thought to exist in the Virginia oyster (Coe, 1938). Additional information, particularly of an experimental nature, will presumably reveal them in other species.

And finally there are the many examples of variations in the expression of sexuality, with intergrading individuals from true males through the various grades of ambisexuality to true females, as mentioned for the species of *Pecten, Ostrea, Teredo* and others. To what extent these differences are due to diversities in the hereditary sexual mechanism and to what extent to environmental influences can be determined only by future experimental evidence.

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Contribution No. 256

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COLLOIDS FROM KELP

Give Rise to a Unique Process Industry

**cessing of colloids from sea-
ds has grown, largely within
past decade, into a sizable
nical industry in this coun-
yet little technical informa-
on this subject has ever
n published. Tonnage-wise,
t important of the seaweed
oids is algin, now produced
n kelp by two basic processes.
ause of their unique proper-
, the alginates have been find-
expanding usage in industry;
ications are that this trend
continue.—*Editors***

PRESENT-DAY USAGE, the term kelp efers to seaweeds of the brown algal : *Laminariales* with large, flat leaf- fronds. Still occasionally used errone- to refer to seaweeds in general, the originally referred to seaweed ash, an rtant source of soda and potash in pe during the 18th and early 19th ries. Scotland alone produced an- y as much as 20,000 tons of kelp In addition, the world's supply of ne was largely derived from seaweed the Chilean nitrate deposits and cer- brines became important sources of chemical.

similar kelp industry was born during ld War I, when this country was striv- to obtain a supply of badly needed sh from the giant kelp of California, rocystis pyrifera. This seaweed also ed as a raw material for making acetone unique fermentation process. How- the use of kelp as a source of potash, ne and acetone was abandoned soon the close of the war and commercial action of these chemicals has never revived in the United States. Only ountries where the living standard is much lower, such as in Japan, can such operations become profitable.

The first seaweed extensively utilized in America was the Atlantic red alga known as Irish moss. Since 1847, this has been harvested regularly for food and certain medicinal and industrial uses. Only in recent years after its colloidal extract, carrageenin, had found extensive uses in various food industries, did the Irish moss industry become firmly established. In the 1920's, the United States gave rise to two other seaweed industries: an agar industry* and a revived kelp industry manufacturing algin. Both were based principally on California seaweeds.

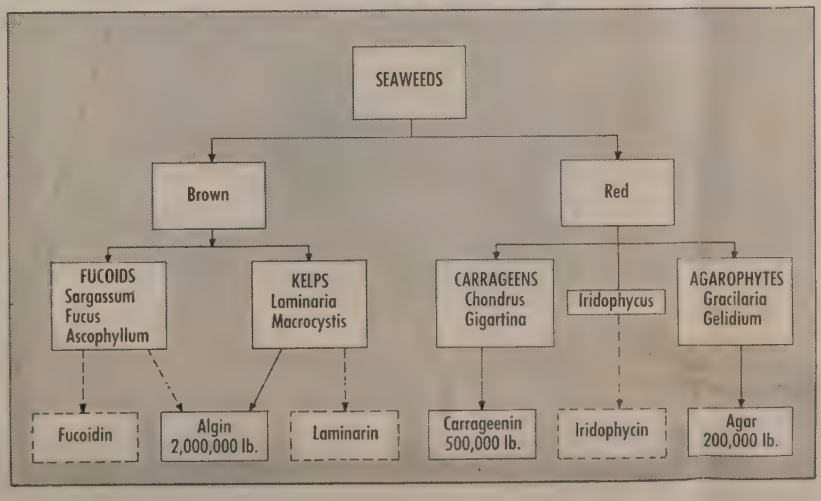
Agar and algin, like carrageenin, are colloidal substances valuable for their unique properties. Algin is important as a suspending, thickening, emulsifying, stabilizing, and water-holding agent. Thus, with the exception of a few firms producing kelp meal for stock feed and pharmaceuticals for human consumption, the present-day American seaweed industry is essentially concerned with the extraction and purification of these seaweed colloids. Fig. 1 shows such colloids now produced commercially in this country, the seaweed from which each is derived and the approximate annual production. The principal commercial producers of these and related seaweed products are listed in the accompanying table.

AMERICAN ALGIN INDUSTRY

In commerce, the term algin refers specifically to soluble alginates, especially sodium alginate and to a less extent, ammonium alginate. In a broader sense, it is used as a general term to refer to all alginous products, the acid as well as its salts. Being chemically unstable, alginic acid itself has few direct uses in industry. The most useful alginous compound is sodium alginate, although the ammonium and calcium salts are also produced commercially in large quantities.

The algin industry in this country was founded at San Diego, Calif., in 1926 by a firm which, after a few changes of name, is now known as the Kelco Co. By virtue of its intensive research and development work, this firm made considerable improvements in the manufacturing processes, de-

Fig. 1—Colloids now produced commercially in this country with the approximate annual production of each; products of possible commercial value which might be produced are indicated by broken lines



* A series of articles on the American agar industry appeared in the January, February and March 1945 issues of *Food Ind.*—*Editor.*

ntribution from the Scripps Institution of nography, New Series, No. 256.

veloped new uses for its products, especially as a stabilizer in making ice cream, and achieved commercial success. It is responsible for the great majority of the algin output in this country and is probably the largest algin producer in the world.

Another firm, established about six years ago as the Algin Corp. of America, has its plant located at Rockland, Me. Like the West Coast concern, this firm produces a highly purified algin. Crude alginous products are made by two other firms especially to serve in feed-water treatment.

United States production of algin in 1941 was estimated by Scheffer (*Fishery Market News*, June 1943, pp 1-6) to be worth $1,500,000, representing probably about 2,000,000 lb. The algin may be in the form of crude products selling for as low as 5c. per lb., alginous pastes for water treatment selling at 7c., and as pure algin selling at $0.80-1.00 per lb. Production data since the outbreak of the war have not been released. It is believed that because of the war requirements, algin production has greatly increased.

HARVESTING KELPS

On the Atlantic Coast of America and Europe, two kinds of kelps are utilized: the horsetail (or digitate) kelp, *Laminaria digitata*, and the broadleaf (or sugar) kelp, *Laminaria saccharina*. These are harvested with a grapple hauled at a depth of 12-15 ft. by a power boat. To a lesser extent, they are obtained by hand dragging from a dory. The harvesting season extends from June to December.

Macrocystis pyrifera is the only kelp used by the Pacific Coast industry, although there are three other giant kelps worthy of being exploited. The *Macrocystis* is truly a "giant" kelp and is undoubtedly the largest seaweed known, growing to over 100 ft. in length and forming extensive beds several square miles in area. It has been estimated that more than 30,000,000 tons of fresh kelp could be harvested annually on the Pacific Coast south of Point Conception, Calif. This figure appears to be much too high, since the highest annual yield so far was only 394,974 tons in 1917. At present, probably about 60,000 tons are harvested annually in this area.

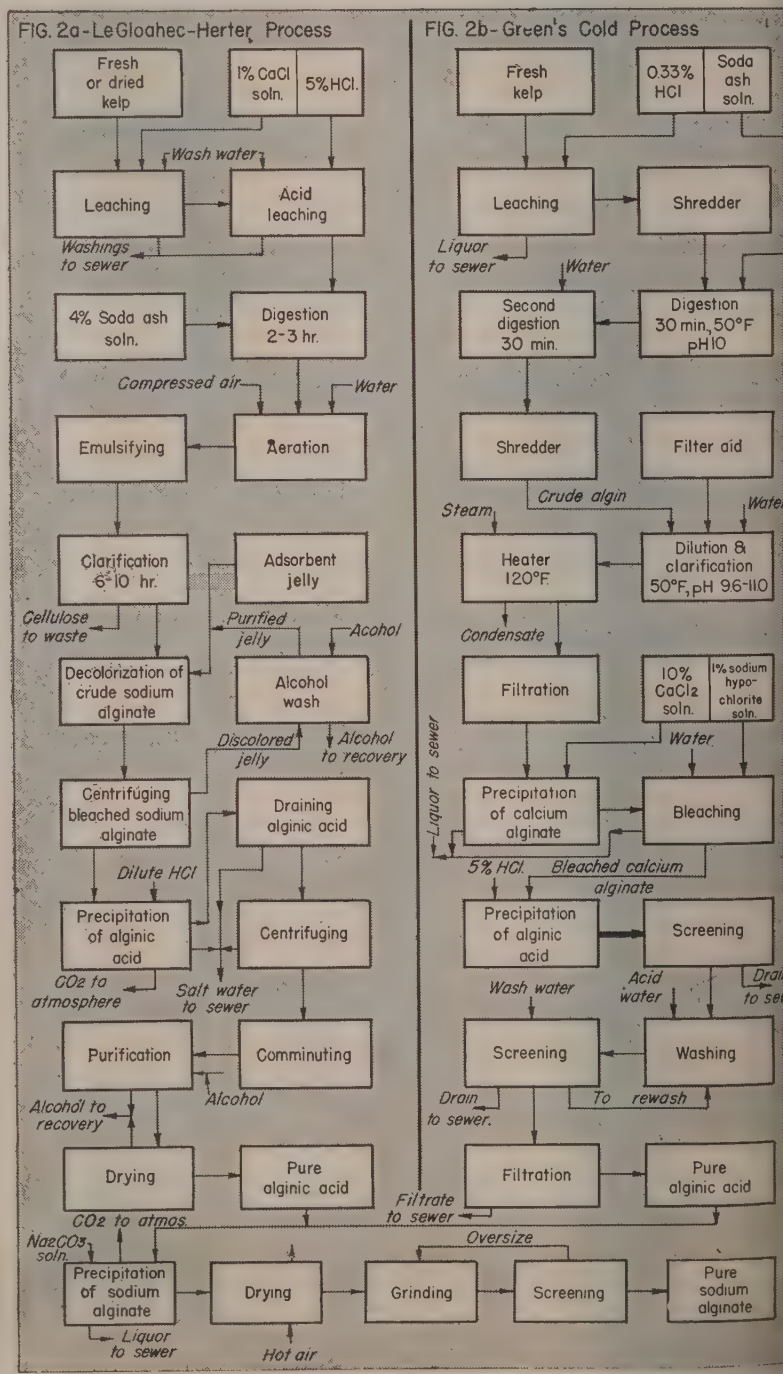
Early methods of harvesting the giant kelp were inefficient and required much human labor until the mechanical harvester was developed. This machine, a major contribution to the success of the Pacific kelp industry, is a motor run barge equipped with a modified mowing machine having a horizontal blade at a depth of about 4 ft. below the surface of the water. An endless chain elevator hoists the kelp on board. The harvester is placed in the bow, with the blade cutting directly ahead of the boat. The knife, generally 10-20 ft. wide, is considerably shorter than the beam of the boat. The elevator, which is as broad as the swath, has its lower sprocket wheels immediately back of the cutter bar. It is driven at rather high speeds so as to pick up the cut kelp before the waves wash it away. A knife at each end of the elevator and parallel with it serves as an edging device to cut the kelp clear at the sides.

A barge of this type can harvest as much as 300 tons of fresh kelp at a single load. Harvesting is carried out on the Pacific Coast in calm weather through the year. By cutting the beds in rotat these can be worked periodically to as a sustained yield.

Since the discovery of algin was repo by the English chemist E. C. C. Stan in 1883, it has been manufactured es tially by the same basic principles: ext tion of algin by alkali and precipitatio alginic acid with a mineral acid.

In Stanford's original "wet" proc kelp was treated with cold water to

Fig. 2—Generalized flowsheets of the two basic processes now used in th country for the manufacture of alginic acid and algin



ve the potash, iodide and other soluble
rganic salts. The residual kelp was
n digested either cold or warm for 24
with 10 percent of its weight of soda
. The resulting glutinous mass was
ered to remove cellulose and foreign
terial. Hydrochloric or sulphuric acid
s added to the filtrate, precipitating
inic acid in light grey, gelatinous flocs
ich were washed and pressed in a
oden screw press to a compact cake re-
mbling new cheese. Sodium alginate
s obtained by soda ash treatment of the
inic acid. When dried, it was in the
m of thin, almost colorless sheets that
embled gelatin but were very flexible.
An interesting and unique process was
d by the Hercules Powder Co. in San
go during World War I. Kelp was
mented to obtain calcium acetate and
ical acetone. The unfermented por-
n of the kelp was then used for the
nufacture of algin by a procedure simi-
to the original Stanford process. Potash
l iodine were also byproducts of this
eration. However, uses of algin at that
ne were still very limited so that soon
er the war the kelp factories ceased
erations and domestic algin production
s suspended until 1926.
Stanford's original process has naturally
dergone a series of improvements by a
mber of investigators. At the present
ne, there are two basic patented proc-
es in commercial use in this country—
een's cold process used by the Kelco
. in San Diego, Calif., and LeGloahec-
rter's process used by the Algin Corp.
America in Rockland, Me. Both of
se processes have, of course, been modi-
l to some extent by the present pro-
cers.

GREEN'S COLD PROCESS

The "cold" process of Green (Fig. 2b)
revealed in U. S. Patent 2,036,934, is
racterized by the fact that it is largely
ducted at the relatively low temperature
50 deg. F. Freshly harvested kelp is
ed in a leaching tank with cold water
viously acidulated to 0.33 percent hydro-
oric acid. The kelp is left in this acid
h water from one to several hours until
salt content is reduced to 5-15 per-
t. The liquid is then drained off and
arded.
eached kelp is chopped into convenient
s fed to a hammer mill shredder, and
n placed in a digestion tank containing
50 lb. of soda ash in solution per ton
reshly harvested kelp. The pH is con-
led at about 10; digestion is usually
pleted in 30 min. The kelp is further
sted by a similar process for another
hour. The resulting pulp is again
ed through a hammer mill shredder
six volumes of treated water added.
pH is maintained at 9.6 to 11. In
s where crude sodium alginate is satis-
ory, the fibrous material is dried and

Producers of Seaweed Colloids and Related Products in the United States.[1]

Name of Firm	Location of Plant	Product	Seaweed Used
Agar Co. of California	Orange, Calif	Agar	Gelidium
Agar Products Co	Los Angeles, Calif	Agar	Gelidium
Algin Corp. of America	Rockland, Me.	Algin	Laminaria
American Agar & Chemical Co	San Diego, Calif	Agar	Gelidium
W. H. & L. D. Betz Co	Rockland, Me.	Algin paste	Laminaria
Dental Research Co	St. Petersburg, Fla	Kelp tablets	Macrocystis
Bowey, Inc	Bath, Me.	Carrageenin	Chondrus
Feedwaters, Inc	New York, N. Y.	Algin paste	Laminaria (imported)
Sperti, Inc	Jensen, Fla	Agar	Gracilaria
Kelco Co	San Diego, Calif	Algin Kelp meal	Macrocystis
Kraft Cheese Co	Chicago, Ill.	Carrageenin	Chondrus
Krim-Ko Co	Scituate, Mass	Carrageenin Agar	Chondrus Gracilaria
Northwest Kelp Co., Inc	Anacortes, Wash	Kelp meal Kelp tablet	Nereocystis
Pacific Agar Co	Whittier, Calif	Agar	Gelidium
Philip R. Park, Inc	San Pedro, Calif	Kelp meal Kelp tablet	Macrocystis
Roselle Agar Gel Co.[2]	Jensen, Fla.	Agar gel	Gracilaria
Van Sant, Inc	Beaufort, N. C.	Agar	Gracilaria
Walsh Kelp Laboratory	San Diego, Calif.	Kelp tablet	Macrocystis
Jacque Wolf & Co	Passaic, N. J.	Carrageenin	Chondrus Gigartina (imported)

[1] Firms engaged only in harvesting and curing seaweeds not listed. [2] Production suspended in 1943. [3] Still in pilot-plant stage, expected to start production soon.

sold as such. For most purposes, however, a highly purified product free from cellulose and other impurities is required.

For a pure product, the crude liquor is pumped into a clarification tank and a filter aid, such as diatomaceous earth, added. The supernatant liquor is filtered through an ordinary mechanical filter press. The temperature may now be temporarily raised to about 120 deg. F. to aid filtration. Other methods of clarification that can be used include centrifuging, vacuum filtering, sand filtering or settling of the cellulose material.

Filtered liquor is slowly added to a 10-11 percent calcium chloride solution under constant agitation. Calcium chloride is used in the proportions of about 100 lb. to 8 tons of the alginate liquor. When agitation stops, precipitated calcium alginate gradually rises to the top. The remaining liquor, containing water soluble salts and organic matter, is drained off.

More water is now added to the precipitate in the same tank and a bleaching agent such as sodium hypochlorite introduced. The amount of hypochlorite added depends on the color of the crude product; generally 1 percent is sufficient. Excessive bleaching will have an adverse effect on the final product.

PURE ACID FORMED

Bleached calcium alginate precipitate is separated from the water and introduced into a 5 percent hydrochloric acid solution. About 42 parts of the acid solution is used for each part of alginate. The acid converts the calcium alginate into fibrous alginic acid. The slurry is passed through a screen to remove excess acid and calcium chloride resulting from the chemical reaction. The drained alginic acid precipitate is introduced into a second tank of acidulated water, agitated, then pumped over another screen. This treatment is repeated until the precipitate is washed free of calcium salts. Enough treated water is used in each washing to raise the pH above 1.9 and simultaneously to reduce the amount of calcium in the product.

Purified alginic acid is filtered and stored in a refrigerated room or converted into the sodium or other salts by treating with the corresponding carbonate, oxide or hydroxide. The alginate thus formed is dried by standard methods, ground, screened and packaged or mixed with other ingredients to form one of several commercial products. The California concern makes at least six different kinds of alginate products, each for certain specific uses.

LE GLOAHEC-HERTER PROCESS

The LeGloahec-Herter process, as revealed in U. S. Patent 2,128,551, takes advantage of the fact that a dilute solution of alkaline earth salts such as calcium chloride will dissolve laminarin, mannitol and other salts in the kelp without any harmful effect on the algin.

Kelp used in this process (Fig. 2a) may be freshly harvested or air dried. To one volume of dried kelp, three volumes of 0.8-1.0 percent calcium chloride solution are added. Lixiviation may be carried out hot or cold, the latter being preferred. Leached kelp is then washed with softened water to remove the calcium chloride as well as the remainder of the laminarin, mannitol and other salts. Washing is stopped when the wash water contains about 0.5 percent soluble matter. The washed kelp may be subjected to an additional treatment with 5 percent hydrochloric acid to dissolve any residual alkaline earth salts. It is then washed with softened water before digestion.

To one volume of the well-lixiviated kelp, two volumes of 4 percent soda ash solution are added. Digestion may be performed in any suitable vessel, the mixing being helped by beaters such as those commonly used in pulp making. Maceration is continued until the cellulose is reduced to fine particles and a homogeneous paste obtained. This will take about 2 hr. at

104 deg. F. and about 3 hr. at room temperature.

The kelp paste is diluted with water in the ratio of 3:7. The mixture is beaten to a homogeneous suspension and air introduced through fine apertures to stir up the whole mass vigorously. It is claimed that oxygen in the air helps to make a product of high viscosity. If oxidizing agents such as ozone or hydrogen peroxide are introduced mechanical agitators are used. The liquor is then passed continuously at high speed through a centrifuge which charges it with air bubbles. The resulting emulsion is conveyed to a clarification tank where, after standing for 6-10 hr., the cellulose particles agglomerate to a compact floating cake. The clarified liquor can then be removed without difficulty.

COLOR ADSORBED

Clarified crude liquor, still colored by seaweed pigments, must be purified to yield a white product. An adsorbent jelly made of hydrated alumina, gelatinous silica and aluminum alginate is preferred, although other similar ones can be used. The jelly is added to the colored liquor in about 20-25 percent of the weight of dry alginous material. The mixture is stirred and the pigments soon adhere to the jelly. This can be removed by centrifuging and reclaimed by various methods, such as by washing with alcohol or other organic solvents.

The liquor is now clarified and freed from pigments and other impurities. Addition of a strong acid such as hydrochloric maintained at a pH of 2.8-3.2 will precipitate alginic acid. The mineral acid and the alginous liquor are introduced separately to meet in a mixing baffle, slightly inclined inside a tank. The precipitate flows at once to the adjoining tank, thus minimizing contact with fresh mineral acid, which tends to have an adverse effect on the final product. Carbon dioxide evolved from the reaction between soda ash and hydrochloric acid helps the precipitate of alginic acid to float and thus overflow into the next tank.

This precipitate of alginic acid is placed in baskets and allowed to drain. Freed from the remaining liquor by pressing or centrifuging, it is comminuted and further purified by washing with solvents such as ethanol in a vessel provided with a filter plate. Purification of precipitated alginic acid by ordinary dialysis or by electrodialysis has been suggested.

Purified alginic acid, containing some adhering alcohol, is dried in a specially constructed oven at 150-170 deg. F. A method of purifying and drying the alginic acid in special rotating drums has been suggested. In both cases, the alcohol may be reclaimed. Alginic acid is converted into its sodium or other salts by the regular processes.

Methods for the recovery of laminarin and iodine are also patented (U. S. Patents 2,188,092 and 2,233,787). In another process (U. S. Patent 2,163,147) for improving the decolorization of the alginous material, formaldehyde, tannic acid or other protein coagulants are added to the soda-digested kelp. The proteinaceous material coagulates and adheres to the cellulose, while the seaweed pigments become fixed to this coagulated mass. Chlorophyll and other plant pigments may then be recovered if so desired. Some 22 lb. of commercial formaldehyde is added to 2.5 tons of water for each ton of demineralized kelp. The mixture is allowed to stand for about an hour. The treated kelp is then taken out and stored for 15-21 days, causing substantial fixation of the colored matter on the protein-cellulose mixture. When soda ash solution is added to the kelp, it dissolves only the alginous matter, which can thus be separated from both the cellulose and the pigments. The process from this point is the same as already described except that decolorization by alumina-silica-alginate jelly is omitted.

Thus the process used by the Algin Corp. of America differs from that of the Kelco Co., as revealed by their patents, in four main points: (1) Dilute calcium chloride solution is used in the leaching, (2) clarification is done by a special aeration and centrifuge system instead of by filter aids and filter presses, (3) precipitation of calcium alginate is omitted, and (4) to decolorize the product, either a pigment-adsorbent jelly or a protein coagulent is used.

WHERE ALGIN IS USED

Because of its unique and useful properties as a colloid, algin has been enjoying a steadily expanding market during the last decade. There is little doubt but that its properties as an emulsifying, suspending, gelling and bodying agent will lead to an increasing usage in industry.

Largest single present use of algin in the United States is as a stabilizer to impart smooth body and texture to ice cream and to prevent coarsening during storage due to the formation of large ice crystals. According to one estimate, more than 50 percent of the factory-made ice cream in this country is stabilized with a special alginous product under the trade name of Dariloid. Being nutritive and not an allergen, algin is used extensively in food industries in the preparation of cakes, jellies, icings, whipping cream and chocolate milk.

A very important use of algin is as a latex creaming agent in the manufacture of natural rubber. Ammonium alginate, regarded as the best substance for this purpose, is said to be used similarly in the processing of synthetic rubber. Both ammonium and sodium alginates are widely used as suspending and emulsifying agents in the manufacture of casein emuls paints. For preventing the encrustat of boilers, sodium alginate is useful si it precipitates calcium salts present in water. The precipitated calcium algin forms globular flocculent masses and velopes other sediments to give a soft pa sludge which can be blown out of boilers at regular intervals.

Use of algin in dental impression ma rials is a recent development as a result the agar shortage, yet its merits for t purpose have been firmly established. Th is no doubt that as a dental material, al has already passed the agar-substitute st and is here to stay. Another recent use algin is to cover and protect dentures m of acrylic resin. Because of certain vantages over the tinfoil formerly used this purpose, algin will undoubtedly come a standard dental coating mate in the future.

MANY APPLICATIONS

Algin serves in various pharmaceut and cosmetic preparations as an emuls ing, suspending, gelling and bodying age It has been used as a component of fanilimide and similar ointments. To so extent, algin has replaced tragacanth other natural gums in the preparation greaseless lubricating jellies. It is used a vehicle for hand lotions of the saponi type and is a base for various creams toothpastes.

As a sizing material algin is valua being superior to starch as it fills the cl better, is tougher, more elastic and g farther than starch or gum. As soon the sodium alginate has impregnated cloth it can easily be made insoluble, i desired, by treatment with dilute ac lime water or metallic salts. Ammonia aluminum alginate can be used in preparation of waterproof fabrics sinc becomes insoluble after drying. Algi quite extensively used as a thickener printing pastes. In the form of trietha lamine alginate, it is used for coating s surfaces. In recent years, great inte has been shown in utilizing alginate fi as textiles, and specially treated algin fi have already found uses because they alkali-resistant and fireproof. Beryll alginate fibers are employed in camouf nettings.

Among the many uses of algin, dorm and active,* are the preparation of retarding compounds, insecticide spr can-sealing compounds, oil well dril mud, storage batteries, varnishes and dressing of mildew-resistant canvas burlap. It is used to a small extent clarifying liquor, finishing leather, in making color-adsorbing materials.

* An extensive discussion of the history, erties and uses is given by the author in the coming Vol. VI of Jerome Alexander's "Co Chemistry" to be published this year by the R hold Publishing Corp. See also pp. 18-19 Gregory's "Uses and Applications of Chemi and Related Materials" (Reinhold Publis Corp.) for a classification of algin uses.—Ed

Contribution No. 257

(Reprinted in U. S. A. from *Transactions* of 1944
of the American Geophysical Union)

RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL, 1943, TO APRIL, 1944

H. U. Sverdrup and Staff

(Contribution from the Scripps Institution of Oceanography, New Series, No. 257)

Again there is little to report to the American Geophysical Union because nearly all the activity in physical oceanography at the Scripps Institution has been in connection with special war projects and results can not as yet be discussed.

G. F. McEWEN has critically reviewed manuscripts and earlier publications in order to indicate appropriate corrections and revisions. For example, extensions of his work on evaporation and mixing, published in 1929, require a computation of the preliminary mathematical tables in the appendix of that work with the aid of newly developed formulas and the extensive fundamental tables recently prepared by the Federal Works Agency (Mathematical Tables Project). This computing is more than 95 per cent completed and the tables may be of use in other researches.

Again, a manuscript is in preparation on the relation of surface ocean-currents to surface temperatures. This is designed to serve as a guide in making extensive applications later, and will include all necessary tabulations and working diagrams.

In compliance with requests for extending the tables by McEWEN in his publication on the Significance of differences (1929), certain practicable methods have been explained of approximating to the results desired for values of the numbers of observations not included in the publication. This year, new and accurate methods of making such computations have been developed that depend upon the tables by PEARSON on the Incomplete beta-function, recently available. Either mimeographed or printed copies of this supplementary paper will soon be prepared.

Regarding the problem of horizontal dispersion of material from an initial source, circular in form, a new and much more satisfactory solution has been obtained, having an error of less than one per cent. This method can be readily applied with the aid of tables or diagrams to be prepared.

The usual observations of temperature, salinity, and weather at our six shore-stations and supplementary observations from United States lighthouse tenders have continued. There were about 1800 salinity observations, 1800 sea-temperature observations, and 1500 wind-observations. Continuous barograph- and pyrheliometer-records and daily observations of humidity and precipitation were maintained at the Scripps Institution.

E. G. MOBERG reports that owing to the lack of laboratory assistance and facilities for obtaining offshore observations or water-samples no important amount of laboratory work has been done. However, nearly all the working space, as well as much of the laboratory equipment, has been in nearly constant use by other members of the Institution's staff or by visiting investigators, to some of whom advice or assistance has been rendered. One of the laboratories, together with apparatus and supplies, has been used by V. SCHEFFER (until January) and Mr. SENN of the United States Fish and Wildlife Service in conducting research on the preparation and properties of agar, the constant-temperature room has been used by C. K. TSENG in carrying out experiments on the growth of Gelidium under controlled conditions of light and temperature. The carbon-dioxide changes in the growth medium of the Gelidium during these experiments were measured by Mrs. SWEENEY who was provided with laboratory space and apparatus for this purpose.

Throughout the year work has been done on field- and laboratory-data previously obtained and it is expected that in the near future some papers based on these data will be ready for publication. Among the subjects dealt with may be mentioned potentiometric methods for determining the salinity of sea-water; the variation, local and according to depth, of the calcium-content of sea-water in several extensive areas of the northeastern Pacific Ocean; and the dynamical and chemical material resulting from the cruises in 1941 of the E. W. Scripps.

Scripps Institution of Oceanography, University of California,
La Jolla, California

Contribution No. 259

Reprinted from Science, June 15, 1945, Vol. 101, No. 2633, pages 597–602.

THE TERMINOLOGY OF SEAWEED COLLOIDS[1]

By Dr. C. K. TSENG
SCRIPPS INSTITUTION OF OCEANOGRAPHY

E the outbreak of the war, there has been a erable interest among some of the United s in investigating and developing their seaweed es. The principal stimulus, in most instances, en an agar shortage. In 1940, America had a agar factory, which made 24,000 pounds of There are now four factories[2] actively engaged industry with a combined production capacity ut 200,000 pounds per annum. The principal hytes are *Gelidium cartilagineum* from Cali- and Baja California, Mexico, and *Gracilaria voides* from Beaufort, N. C.[3]

interest shown in agar does not stop there; it s to related seaweed colloids capable of serving stitutes for agar. One of these is carrageenin, lly known in commerce as Irish moss extract. ncipal source is carrageen, better known as oss (*Chondrus crispus*), which is now obtained e quantities from Massachusetts and Maine in ited States and from the Maritime Provinces ada. The name carrageen is also applied to *na stellata* (*G. mamillosa*), commonly harvested r with the *Chondrus* and used similarly. Pre- the production of Irish moss extract was small, since most consumers preferred to buy weed and make their own extract. In recent there has been a great demand by various in- s for a highly purified, standardized product nce the production of the extract is greatly ed. At present there are in the United States t three companies producing the extract and others processing carrageen. It has been esti- hat the United States made about half a million of the extract in 1944.

other seaweed colloid which has received con- le attention lately is algin, an alkali-extracted charide from various kinds of kelps and . In the United States the kelps utilized are *ria digitata* (horsetail kelp) and *L. saccharina* leaf kelp) from Maine and Nova Scotia, and *Macrocystis pyrifera* (giant kelp) from California. Although relatively young, the algin industry has been growing steadily and fast, especially in America and recently in Great Britain. This is shown by the fact that in 1941 the United States produced about one and one-half million dollars worth of algin.[4] War has greatly stimulated the growth of this industry, and undoubtedly much more algin is now being produced than in the pre-war period. There are four concerns in the United States making algin and its derivatives.

While seaweeds have served rather extensively as food in the Orient, they have never been as popularly utilized for culinary purposes by the Occidentals. In the past, soda, potash and iodine had been extracted, and organic solvents such as acetone derived from seaweeds on a large scale in America and Europe. In countries enjoying relatively high standards of living, these materials can no longer be produced profitably from marine plants, since they can be obtained more cheaply elsewhere. The important seaweed products in recent years have been the polysaccharides agar, algin and carrageenin. Because of their unique colloidal properties, these substances are valuable for special purposes and, in spite of their relatively high cost, have been extensively used in food, pharmaceutical, cosmetic and other industries. Agar, for instance, is still the undisputed material for preparing solid bacteriological culture media, and is extensively employed in bakery products, health food and dental impression materials. Algin is most valuable as an ice-cream stabilizer, and is regarded by dairy experts to be as good as, if not better than, gelatin, which was the standard stabilizer until recently. Carrageenin is now the standard suspending agent for cocoa particles in chocolate milk preparations. To the unique properties of these seaweed colloids the modern seaweed industry in the United States owes its existence and its present prosperity.

The increasing interest in seaweed polysaccharides will certainly lead to more research activities in the studies of these products and their sources from biological, chemical and technological points of view.

[1] tributions from the Scripps Institution of Oceanog- New Series No. 259.

[2] re are three more factories, still in the pilot plant ut expected to produce agar soon.

[3] K. Tseng, *Food Industries*, 17: 140, 1945.

[4] V. B. Scheffer, *Fish. Mark. News*, 5(6): 1, 1943.

The progress of such researches, however, will be greatly hindered by the loose and inconsistent, sometimes inaccurate, use of terms applying to these colloidal substances and their sources. It is the firm belief of the writer, therefore, that such confusion should be clarified, and the application of the different terms involved be standardized as far as our present knowledge of the sources and chemistry of these products permits. Whenever necessary, new terms should be introduced.

Phycocolloids. In the early days, when agar was the only commercial seaweed colloid, it was variously called "vegetable isinglass" or "vegetable gelatin." These terms have not been used in recent years, since it is well known that agar and the other commercial seaweed colloids are all polysaccharides and are not nitrogenous compounds as they were first thought to be. At present, they are commonly called "seaweed gums" and "seaweed mucilages" by various authors.

Gums occur chiefly as exudations on the barks of trees or on fruits, and mucilages are commonly extracted from seeds. Seaweed colloids, however, are chiefly cell wall constituents, comparable to the pectins of the land plants. They should therefore not be grouped with the gums and mucilages, in spite of certain resemblances, since they differ from the land plant products not only in origin, but also in chemical nature.

Phylogenetically, the primitive marine plants known as the brown and the red algae, from which we derive our agar, algin and carrageenin, are not directly related to the modern highly evolved land plants. There are consequently numerous differences between the plants of the sea and those on the land in their chemical constitution. For instance, it has been well established in recent years that chlorophyll *b* is not present in the brown and the red algae, which have, instead, chlorophyll *c* and *d*, respectively.[5] The kinds of reserve food of these seaweeds are also different from those of the land plants. The seaweed polysaccharides are consequently expected to be different chemically from their counterparts in the land plants. This is quite true, so far as our limited knowledge of their chemistry is concerned. The gums and mucilages are polyuronides consisting of several types of much branched monosaccharide units. The seaweed colloids, on the other hand, consist of generally one or two types of simple monosaccharide units, and with the exception of alginic acid, are not polyuronide. Although alginic acid resembles the gums in being a polyuronide, it is quite unique in being composed exclusively of mannuronic units.

[5] H. H. Strain and W. M. Manning, *Jour. Biol. Chem.*, 144: 625, 1942; W. M. Manning and H. H. Strain, *ibid.*, 151: 1, 1943.

That the seaweed polysaccharides should be d from the gums and mucilages has also been ad by Norman,[6] who groups these marine produc rately under "gel-forming substances." It sh noted, however, that, strictly speaking, not all t mercial seaweed colloids are gel-forming. Mo the use of such a complex term is rather incon The new term "phycocolloid"[7] has therefore be posed to designate the polysaccharides which rived from the brown and the red seaweeds able to form colloidal systems when dispersed in

Gelose. Payen[8] proposed the term "gel designate the refined extract from "mousse de or "Chinese moss," under which name agar was when first introduced into France from China Later, various authors used the same term t to carrageenin. "Gelose" is a well-selected te is worthy of being kept to designate collectiv red algal extracts, such as agar and carra aqueous solutions of which are able to form or less firm jelly. It can not be used to inc the seaweed polysaccharides, however, since s them, the alginates, for instance, are not stric forming substances.

Agar. The writer[9] has previously pointed existing confusion in the usage of the word "a "agar-agar." To avoid using the same word or three different meanings, the writer has p the word *agarophyte* to refer to the agar-bear weeds and to restrict the use of the word aga sively to the dried extract.

Chemically, agar is the sulfuric ester of galactan. It consists of a long chain of *d*-pyranose residues, attached by 1:3-glycosid ages. This chain is terminated at the reduc by one residue of *l*-galactopyranose. Attache rest of the chain through carbon atom 4, this tose residue is esterified at carbon atom 6 with acid.[10] There are probably as many as 53 g units to each SO_4H group, and at least 140 su to each nonreducing end group.[11] Our presen edge of the chemistry of agar is still inc Moreover, with one exception,[11] the previous of the agar employed in the chemical studie known. While these investigators undoubted

[6] A. G. Norman, "The Biochemistry of Cellulo uronides, Lignin," etc., 1937, Oxford.

[7] From Greek φῦκος (seaweed) and κόλλα (glue C. K. Tseng, "Phycocolloids: Useful Seaweed charides" in Jerome Alexander, "Colloid Che vol. VI (in press), Reinhold Publishing Company

[8] M. Payen, *Compt. rend.*, Paris, 49: 521, 1859.

[9] C. K. Tseng, *Sci. Monthly*, 58: 24, 1944.

[10] W. G. M. Jones and S. Peat, *Jour. Chem. So* 225.

[11] V. C. Barry and Thomas Dillon, *Chem. a* 1944: 167.

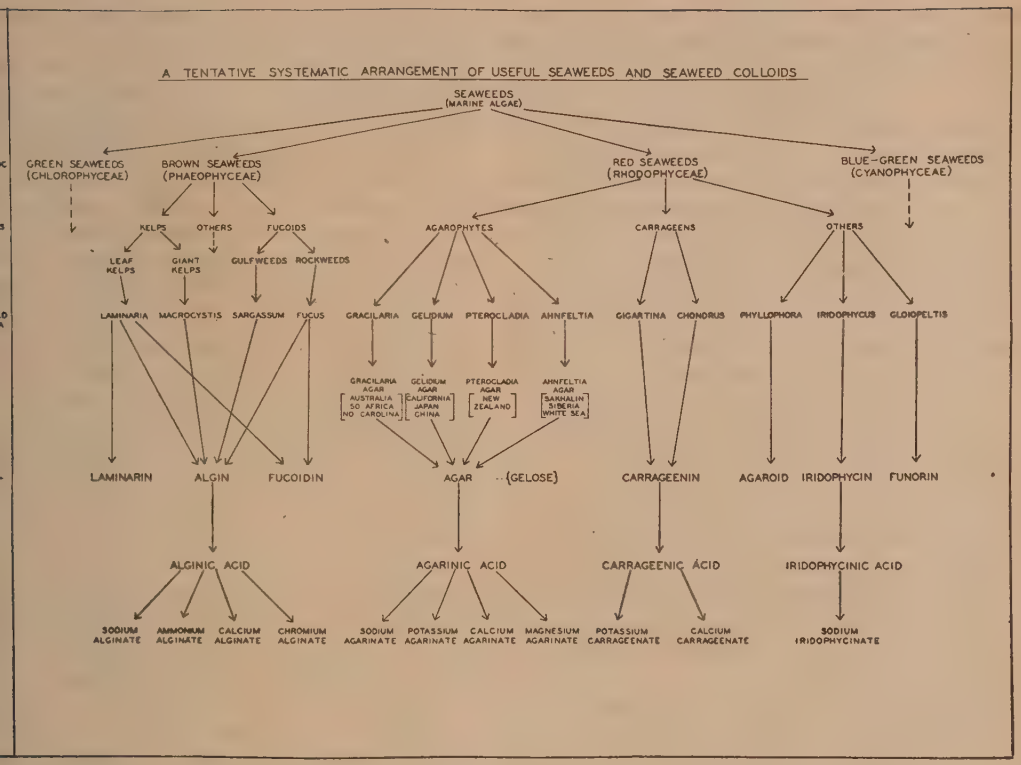


FIG. 1

se agar, it should be noted that the Japanese is not a pure agar from *Gelidium Amansii* It probably consists of a mixture of seaweed charides, since the Japanese use several other ae, besides the *Gelidium,* in their agar manu-

agar which scientists have been using is prin- prepared from species of *Gelidium* in Japan fornia. Those which are made in North Caro- outh Africa, Australia, New Zealand, Russia khalin Island come from other sources. It is, not definitely known whether the so-called agar ources other than species of *Gelidium* are the hemically as the "standard" agar. They do e the agar made from *Gelidium* in their physi- perties. For instance, they are soluble in hot in cold water; they all yield firm gels in dilute solutions of one or two per cent.; they have contents, generally less than 5 per cent.; and ing temperatures of their sols, as well as the temperature of their gels, are reasonably each other. It is proposed, therefore, to all of them tentatively as agar, and to desig- em as Gelidium-agar (California, Japan and Pterocladia-agar (New Zealand), Gracilaria-agar (Australia, South Africa and North Carolina) and Ahnfeltia-agar (Sakhalin Island and White Sea, Russia).[12]

Any attempt at a critical definition of agar is, of course, premature. Nevertheless, a tentative definition will help in the clarification of the conception of agar. The writer has previously proposed such a definition.[9] It is slightly modified and presented as follows: The dried amorphous, gelatin-like, non-nitrogenous extract from *Gelidium* and other agarophytes, being the sulfuric acid ester of a linear galactan, insoluble in cold but soluble in hot water, a one per cent. neutral solution of which sets at 35° to 50° C to a firm gel, melting at 80° to 100° C.

It has been observed by various investigators that when agar is hydrolyzed with an acid, a free "agar-acid" is formed which fails to gel until neutralized by the addition of a base. It is also quite generally accepted that in the natural condition agar probably occurs as the calcium salt, or a mixture of calcium and magnesium salts of this free "agar-acid." Fair-

[12] This is better known as Sakhalin agar, since it was first extracted from *Ahnfeltia plicata* from Sakhalin Island (or Karafuto) by a Japanese about forty years ago. The seaweed was subsequently found in large quantity in the White Sea region.

brother and Mastin[13] and Hoffman and Gortner[14] have prepared potassium and other salts of the acid which gel as readily as does the natural agar. For the sake of uniformity of nomenclature, it is here suggested that this "agar-acid" be called agarinic acid, since the term agaric acid has already been used to apply to another totally different compound. Accordingly, the agar as occurring in nature may be regarded as calcium agarinate, and the corresponding magnesium, potassium and sodium salts as magnesium agarinate, potassium agarinate and sodium agarinate, respectively. While these salts are not prepared commercially at present, it is not impossible that they may eventually be made for special uses.

Carrageenin. The name carrageenin was given to the extract from *Chondrus crispus* by Stanford.[15] It was, however, first isolated by Schmidt[16] in 1844. Although carrageenin is a very appropriate term, it has not been well received. Scientists working on this polysaccharide have been calling it under such compound names as "carrageen extract," "*Chondrus* polysaccharides," "Irish moss mucilage," etc. For the sake of simplicity and uniformity in nomenclature, the writer is in favor of using the term carrageenin for this gelose.

Carrageenin resembles agar in a general way, but has a much higher ash content (about 20 per cent.), and requires higher concentrations (3 or more per cent.) to form firm gels. Its gel melts at much lower temperatures (27° to 30° C for a 3 per cent. gel and 40° to 41° C for a 5 per cent. gel).[17] Chemically, carrageenin is similar to agar in being a carbohydrate ethereal sulfate and in containing galactose residues[18] joined by 1:3-linkages. The sulfuric ester group, however, is attached to carbon atom 4, not 6. The galactosidal linkages combining the residues seem to be of the α-type. Like agar, carrageenin is considered to be a cell wall constituent, and is presumed to occur *in situ* as a mixture of sodium, potassium and calcium salts.[19] While the acid is still imperfectly known, it may be conveniently called carrageenic acid. The carrageenin in the natural condition is accordingly a mixture of sodium, potassium and calcium geenates.

Funorin. This term has recently been used to nate the polysaccharide of *Gloiopeltis* (funori in nese),[20] which gives the gluey extract used fo dreds of years in the Orient as a textile-sizing rial. Its exact chemical nature is still unknow

Iridophycin. From a California red alga, *phycus flaccidum*,[21] Hassid has isolated a g ethereal sulfate, which upon hydrolysis give galactose.[22] The name *iridophycin* is tentativel to this polysaccharide for the sake of conv and uniformity. It contains over 25 per cent. which consists chiefly of sodium sulfate. It sumed to be of the 1:4 normal pyranose type stitution, with the sixth carbon atom beari ethereal sulfate group. The free acid has be pared by electrodialysis, and may be termed phycinic acid. The colloid occurs *in situ* prin as its sodium salt.

Agaroid. From Odessa in the Black Sea reg Russians have extracted from the red seawee *lophora*,[23] a substance which was first regard kind of agar. Later, it was named agaroid[24] of certain differences between it and agar. It chemical nature is still not known.

Algin. Stanford[25] reported in 1883 that by ing kelps with sodium carbonate solution, a gl mass was obtained which, when evaporated to d presented "an appearance which is not unli tragacanth." To this new substance Stanfor the name "algin," derived from the word alga term has since been variously used by its dis and others to apply to: (1) sodium salt of t stance; (2) natural state of this substance, according to some, may be the calcium salt; (3) acid; (4) soluble alginates, and (5) alginic a its salts in general. As it is used in commerce "algin" refers to the soluble alginates, es sodium alginate and, to a lesser extent, am alginate. To avoid confusion, the term algin i restricted to sodium alginate, which is the product in all the processes of manufacture an which other alginates are derived. Since "ag

[13] F. Fairbrother and H. Mastin, *Jour. Chem. Soc.*, 123: 1412, 1923.

[14] W. F. Hoffman and R. A. Gortner, *Jour. Biol. Chem.*, 65: 371, 1925.

[15] E. C. C. Stanford, *Jour. Soc. Arts*, 10: 185, 1862.

[16] Carl Schmidt, *Annal. Chem. und Pharm.*, 51: 29, 1844.

[17] Paul Haas and T. G. Hill, *Ann. Appl. Biol.*, 7: 352, 1921.

[18] E. G. Young and F. A. H. Rice have recently reported in *Jour. Biol. Chem.*, 156 (2) 781, 1945, the isolation in considerable quantity of 2-ketogluconic acid as a constituent of carrageenin, in addition to the galactose residues.

[19] J. Buchanan, E. E. Percival and E. G. V. Percival, *Jour. Chem. Soc.*, 1943: 51.

[20] C. K. Tseng, *Sci. Monthly*, 59: 37, 1944.

[21] Erroneously called *Iridaea* (*Iridea*) *laminari* various authors; *cf.* G. M. Smith, "Marine Alga Monterey Peninsula," p. 288, 1944, Stanford.

[22] W. Z. Hassid, *Jour. Am. Chem. Soc.*, 55: 416 *ibid.*, 57: 2046, 1935; *Plant Physiol.*, 11: 461, 1

[23] V. L. Elin, R. Grayerova and G. Fisher, *Bull Issledovatel Khim-Farm. Inst.*, 1931: 140; A. Ko *Khim-Farm. Prom.*, 1934(4): 36.

[24] V. Gryuner and N. Tauson, *Colloid Jour.* (U 2: 783, 1936; V. Gryuner and L. Veronyan, *ibid.*, 1939.

[25] E. C. C. Stanford, *Chem. News*, 47: 254, 188

ageenin" have been accepted to designate respec- the water-extracted colloids from agarophytes arrageens, it is logical to limit the use of "algin" soda-extracted substance, *i.e.,* sodium alginate, kelps. The other alginous products may be ated as ammonium algin, calcium algin, chro- algin, etc. From the limited information we at present, it seems that algin from different s belongs to the same chemical entity.

inic acid is a polyuronic acid with the empirical la $(C_6H_8O_6)_n$. It is composed entirely of nuronic anhydride residues,[26] in which the hy- l groups are attached to carbon atoms 2 and 3, bridge and ring are attached to carbon atoms 5. Although evidence is not yet sufficient to between pyranose and furanose structures, the r is more probable, in view of the large negative on of alginic acid and its resistance towards lysis. Thus, the mannuronic acid units are in such a way that the carboxyl group on each s free to react, while the aldehyde group is ed by linkage.[27] Like agar and carrageenin, is presumed to occur in nature as a cell wall tuent, probably existing as a mixture of the itself and its calcium, magnesium and alkali salts.

inarin. Although laminarin was discovered two years later than algin, being isolated by edeberg in 1885, it has not yet found commer- pplications. Laminarin is the reserve carbohy- of the kelps, analogous to, but different in struc- nd properties from, starch of the land plants. sists exclusively of glucose residues, with the empirical formula of $(C_6H_{10}O_5)_n$. There are probably 16 glucose units, which are combined by 1:3-glycosidic linkages. The linkages in laminarin are regarded to be of the β-type.[28]

Fucoidin. In 1913 Kylin[29] reported that he had extracted from *Laminaria* and *Fucus* a new polysaccharide which he called "fucoidin." A similar water-soluble carbohydrate was isolated from the giant kelp, *Macrocystis pyrifera,* by Hoagland and Lieb[30] in 1915. Fucoidin is presumably a carbohydrate ethereal sulfate, occurring in nature as a calcium salt. On hydrolysis, it gives rise to pentoses and methyl-pentoses, particularly fucose. Like laminarin, fucoidin has not yet found commercial uses.

Classification of phycocolloids. In view of our incomplete knowledge of their chemistry, it is still too early to propose a critical classification of seaweed colloids. It may be said, however, that there seem to be three groups of the phycocolloids. First of all, we have the water-soluble ethereal sulfates as represented by agar, carrageenin and fucoidin; they are similar to the mucilages in some of their properties. Secondly, there are the water-soluble reserve carbohydrates consisting exclusively of glucose units; they are represented by laminarin and occupy a position similar to that of starch in the land plants. In the third group we have the alkali-soluble polyuronides, represented by algin, which are analogous to pectin. The accompanying diagram summarizes the writer's view of the sources of these interesting seaweed colloids, or phycocolloids, and their interrelationship. It is to be noted that there are as yet no commercial colloids extracted from the other two seaweed groups, the green algae (Chlorophyceae) and the blue-greens (Cyanophyceae).

. C. Barry and T. Dillon, in *Sci. Proc. Roy. Dublin* 21: 285, 1936, expressed their conviction that the erizing unit in alginic acid is the complete uronic nd not the anhydride, and hence the empirical for- for alginic acid should be $(C_6H_8O_6 \cdot H_2O)_n$.

. L. Hirst, J. K. N. Jones and W. O. Jones, *Jour. Soc.,* 1939: 1880.

[28] V. C. Barry, *Sci. Proc. Roy. Dublin Soc.,* 21: 615, 1938.

[29] Harold Kylin, *Z. Physiol. Chem.,* 83: 171, 1913.

[30] D. R. Hoagland and L. L. Lieb, *Jour. Biol. Chem.,* 23(1): 287, 1915.

Contribution No. 260

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PLS. 1–3, FIGS. 1–2, AUGUST, 1945

ENTRAPMENT OF AIR IN BEACH SAND

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Contributions from the Scripps Institution of Oceanography
New Series, No. 260

ABSTRACT

Sand holes, sand domes, and cavernous sand are common minor beach features. All appear to be formed by air being forced out of pore spaces in the sand because of the entrance of water. The features may be of some geological significance in determining the order of deposition of steeply dipping sandstones and, if present in great abundance, may be indicative of a marine depositional environment.

INTRODUCTION

It is a common observation that on the upper part of most sand beaches a large amount of air is expelled from the sand when a wave washes up the beach slope. Most of this escaping air forms bubbles which rise through the water as it runs back down the beach slope. Even after the sand surface is re-exposed, air continues to escape for a short time as shown by the continued formation of numerous small holes in the surface, and sometimes by a local doming of the sand surface. In escaping or attempting to escape from the sand, the air may produce sand holes, sand domes, or cavernous sand. Where recognized in ancient consolidated sediments, these features may be indicative of a special environment and have other geological significance.

Sand holes, sand domes, and cavernous sand were studied intermittently over a period of about two years at many beaches near San Diego, Mission Bay, and La Jolla, California. All three features were also found during short visits to be present on favorable parts of other Pacific Ocean beaches at San Francisco, Santa Monica, Long Beach, Huntington Beach, Newport Bay, and Cardiff, California, and at Atlantic Ocean beaches at Martha's Vineyard, Mass.; New London, Conn.; Cape May, N. J.; Norfolk, Va.; San Augustine, Fla.; Miami, Fla.; Bermuda; and Recife, Brazil. Sand holes and either sand domes or cavernous sand were seen on beaches at Woods Hole, Mass.; Manhattan Beach, N. Y.; San Juan, Puerto Rico, Panama, C.Z., and the Salton Sea. On beaches at Key West, Fla., and Galveston, Texas, the features could not be found. Neither were they found on brief examination of beaches of Lake Michigan, Lake Worth in Texas, and small reservoirs in California. It is apparent, however, that the features have very widespread distribution.

The writer is especially indebted to Dr. Martin Johnson and Mr. E. C. LaFond for suggestions regarding origin of the features. Ideas were also contributed by many others during informal discussions.

SAND HOLES

In escaping from beach sand, air usually is concentrated in several steady streams, each emerging from a hole between 1 and 10 millimeters in diameter. On flat parts of a beach where the water runs back downslope slowly, or on the backslope where water may collect in shallow ponds at high tide, most of the air escapes into the water as bubbles. Agitation of the water by the bubbles results in the formation of a crater, commonly about 2 centimeters deep and 5 centimeters wide, at the mouth of the hole. These craters appear to be small-scale relatives of craters formed in mud through the action of escaping gas bubbles as described by Maxon (1940). Another type of mouth consists of a raised rim about 1 millimeter high and 5 millimeters wide closely surrounding the hole. These rimmed openings are some-

times formed when the sand is covered by only a thin film of water. A third type of hole is common on steep parts of a beach where the water runs downslope so quickly that most of the air escapes from the holes directly into air. The mouth of each of these holes is sharp-edged, with no suggestion of a crater or a raised rim (pl. 1, fig. 1). The sharp-edged holes are sometimes formed on gentle slopes also, after the water has run back downslope and bared the sand. Both the cratered and the sharp-edged holes are very common, but the type having a raised rim is rare. All three types are shown in plate 1, figure 2.

On excavating the sand around a hole, one finds that most of the holes are between 1 and 4 centimeters deep. Many have ramifying feeder channels at the bottom, much as described by Palmer (1928).

Somewhat similar holes are formed at the very highest part of beaches by burrowing crustaceans (Emery, 1944). The broad shallow holes formed by drips from ledges, and by raindrops have entirely different characteristics and are not apt to be confused with those caused by the escape of air (Twenhofel, 1932, p. 678).

SAND DOMES

Frequently associated with sand holes are domes or areas where layers of sand are uplifted above an air pocket which has the shape of a laccolith (pl. 2, fig. 1). The sides of the sand dome usually constitute a smooth gentle slope to the highest point at the center of the dome. Occasional small domes, however, have steep abrupt side slopes rising to a flat mesa-like area. The sand domes range from about 2 to more than 15 centimeters in diameter and from a few millimeters to about 3 centimeters in height. The "air laccolith" has approximately the same height, but a somewhat smaller diameter than the domed sand surface. It sometimes caps a feeder hole similar to other sand holes that extend to the surface, but usually there is no trace of a feeder hole. Similar domes have been briefly described by Reade (1884), Palmer (1928), Twenhofel (1932, p. 685), and Johnson (1938).

Sand domes occur chiefly on the upper part of a beach and usually form near the uppermost reach of a wave when the water begins running back downslope. Sometimes successive waves form domes along roughly parallel lines, each line marking the position of farthest advance of a wave. One beach was observed to have seven separate such areas of sand domes.

Almost invariably the sand domes are restricted to beaches having thin layers of coarser sand alternating with layers of finer sand. The "air laccoliths" are formed in the coarser layers (pl. 2, fig. 1). On many beaches the coarser grained layers consist of shell fragments and the finer grained layers of detrital sand of almost the same color. However, some of the California beaches consist of alternating dark and light colored laminae of detrital sand, as described by Thompson (1937). An attempt was made to find the grain size in each type of lamina of the beach near Scripps Institution of Oceanography. Median diameters of 0.190 millimeters for the light colored sand and of 0.165 millimeters for the dark heavy mineral sand were obtained, but because of the impossibility of sampling either lamina without including some sand from the other lamina, the actual size difference of laminae on this beach is greater than these figures indicate. A dye injected into this laminated sand just before it was covered by a wave was later found to have drained downdip 15 centimeters in the coarser laminae in contrast to only 3 centimeters in the finer laminae, thus indicating a differential horizontal permeability. A similar relationship for laminae of dune sand was described by Bagnold (1942, pp. 237, 238).

Where sand domes are formed in beaches composed of alternating dark and light colored laminae, striking patterns are formed after partial erosion of the sand domes, as shown in plate 2, figure 2. Usually the first wave which washes over a newly formed sand dome truncates it at a level even with the gen-

PLATE 1

FIG. 1.—Sand holes in coarse sand beach at south La Jolla, California. Beach slope is about 5 degrees.

FIG. 2.—Sand holes in fine sand beach at entrance to Mission Bay, California. Many of the holes have crater-like mouths. A few other holes are surrounded by small raised rims, and some of the smaller holes have sharp-edged mouths like those of figure 1. Note the sand dome about 20 centimeters right of the knife. Beach slope is 1 degree.

PLATE 2

FIG. 1.—Sand domes exposed in cross-section of well laminated fine sand beach near Scripps Institution of Oceanography, La Jolla, California. Dome at left was formed and the upturned laminae were bevelled. A layer of nearly horizontal laminated sand was deposited, after which the dome at right was formed but not yet truncated. Note the numerous sand domes in the background. Beach slope is about 3 degrees.

FIG. 2.—Surface of the same beach showing appearance of smaller domes which were truncated so that successively deeper laminae are exposed. Domes near bottom have been partly destroyed or buried by later waves. Note the presence of sand holes near the center of some of the truncated domes.

PLATE 3

FIG. 1.—Cavernous sand on ripple-marked fine sand beach near entrance to Mission Bay, California. Cavernous layer is about 5 centimeters thick. Beach slope is 2 degrees.

FIG. 2.—Cavernous sand at same beach in layer 25 centimeters thick. Beach slope is 5 degrees.

eral beach surface. If the height of the sand dome is such that the truncation includes part of a dark lamina, the position of the sand dome is marked by a black spot. If another sand dome is higher, the second lamina of light sand may be exposed, leaving the position of that sand dome marked by a dark ring. Both types of markings are present in the area of plate 2, figure 2. After truncation, the sand domes may be buried by a later fill of sand having horizontal laminae extending across the bevelled edges of the lower tilted laminae (pl. 2, fig. 1). Some of the larger domes collapse after truncation and their position is marked by a slight depression instead of a domed area.

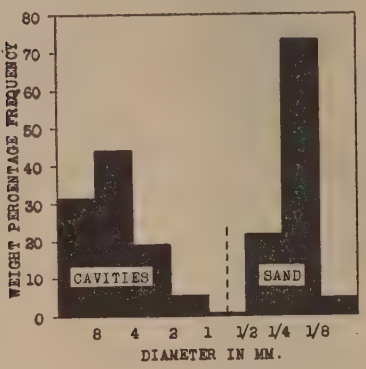

FIG. 1.—Histograms showing size variation of sand grains and of ellipsoidal cavities in sand illustrated in plate 3, figure 2. Note that both histograms show size distribution by weight (or volume) percentage frequency and not by numerical percentage frequency.

CAVERNOUS SAND

In addition to laccolith-shaped air pockets, numerous small ellipsoidal cavities are present in a layer several centimeters thick in many beaches. On some beaches these layers were found to be 20 to 30 centimeters deep (pl. 3, fig. 2). The texture is similar to that of coarse bread. The diameter of these cavities is many times that of the sand grains which form the smooth cavity walls. Careful breaking of lumps of this sand shows that few of the cavities are connected either with each other or with the sand surface. In shape, the cavities vary from spheres to rough ellipsoids elongate in the bedding plane. Where only a few cavities are present, they usually occur in rough alignment along a coarse lamina. Where more abundant, they occur in a layer several centimeters thick and may be independent of laminae.

Mechanical analysis of a typical cavernous sand layer from Mission Bay showed the sand to have a median diameter of 0.190 millimeters. For comparison, the maximum diameter of all cavities exposed by breaking a lump of cavernous sand was measured with a transparent ruler having a millimeter scale. The median diameter based on the diameter frequency distribution of 603 cavities counted is 1.8 millimeters. Since this median diameter is based on the numerical frequency of cavity diameter it is not directly comparable with the 0.190 millimeter median diameter of the sand grains because the latter is based on weight frequency distribution (Krumbein and Pettijohn, 1938, pp. 225–227). Converted to volume (or weight) frequency distribution, the ellipsoidal cavities are revealed to have a median diameter of 5.8 millimeters, or about 30 times the median diameter of the sand grains which form the cavity walls (fig. 1).

The total porosity of the cavernous sand was assumed to consist of the volume of the ellipsoidal cavities plus the normal porosity between tightly packed grains of sand. The aggregate volume of the cavities was measured by compacting underwater a core of the sand 8.2 centimeters in diameter and 10.6 centimeters in length until all settling ceased and no bubbles of air were given off when the sand was stirred by a thin rod. Compaction of the most porous sand found at Mission Bay to a length of 6.8 centimeters showed that the cavities constituted 36 per cent of the volume of the original sand mass. By weighing the wet sand, drying it, and reweighing, the weight of the interstitial water and thus the intergranular pore space was found to be 37 per cent of the compacted sam-

ple, or 24 per cent of the original sample. This method introduces an error of probably not more than 1 per cent because the pore space adjoining one side of each sand grain facing a cavity is included in both measurements. The total original pore space then is 36 plus 24 minus 1 equal 59 per cent by volume.

Cavernous sand, like the sand holes and sand domes, is most common near the upper part of the beach reached by the tide, and the three features are usually closely associated. When covered by high tide, the layers of cavernous sand give out great clouds of bubbles after being walked on or otherwise disturbed. These bubbles obviously are from the cavities as examination of numerous lumps of the sand has revealed only air, never water, within the cavities.

The sand is softest immediately after being exposed by a retreating tide. Apparently the surface tension of the interstitial water is sufficient to hold the sand grains in place around the cavities but is not able to give the mass of sand much strength against local outside forces, so that footprints penetrate almost the entire thickness of the cavernous sand layer. After drying to the stage where little or no interstitial moisture is present, the sand is firmer, supposedly because of deposition of a sea-salt cement between the sand grains. In several instances, the cavernous sand was found immediately underlying a ripple-marked surface (pl. 3, fig. 1). However, it usually underlies a smooth surface and may be buried under several centimeters of firmly packed sand which is separated by a sharp contact and is known to be a more recent deposit. When one walks over a beach having compact sand overlying cavernous sand, the beach may appear quite firm so that light steps leave only shallow footprints. However, if by heavier steps the surface layer is broken, footprints may become very deep.

RELATION TO BEACH CHARACTERISTICS

There is a rough relationship of the sand holes, sand domes and cavernous sand to the size of sand grains. In general, they are present or abundant in coarse, medium, and fine-grained sand, and rare or absent in very coarse and very fine sand. All the features are abundant only at the upper part of the beach reached by high tide. Cratered sand holes are common only on the backslope, while the simple sharp-edged holes are found on all parts of the upper beach, on both flat and steep beaches, and even on vertical erosional slopes. Sand domes and cavernous sand are rare on slopes of more than about 8 degrees. Sand domes are best developed in laminated sand, while both sand holes and cavernous sand are less closely related to laminae.

Although cavernous sand is present on most beaches of intermediate grain size, it usually is far less well developed on beaches exposed to large waves than on the more protected beaches of bays. Typically, the thickness of the cavernous sand layer on beaches facing the open ocean is not more than 4 centimeters, in contrast to layers of 30 centimeters thickness which have been observed in bays.

SAND DUNES

After a heavy (2.5 centimeter, according to U. S. Weather Bureau records) overnight rainfall, the sand of dunes near San Augustine, Fla., was found to be wet to a depth of about 4 centimeters. A number of sand domes were found in the wet layer of sand, and cavernous sand occurred in the flat basins between dunes. When the sand dried during the following day, the domes were destroyed through erosion by wind-blown sand.

LAKE BEACHES

Sand holes, sand domes, and cavernous sand have not been reported for lake beaches so far as the writer is aware. Observations on beaches of Lake Michigan and small reservoir lakes in Texas and California failed to reveal the features. However, sand holes and sand dunes were found on a beach of the Salton Sea after a period of high waves but neither were as abundant as on most marine beaches. It is possible, therefore, that they may form on beaches of large lakes during times of occasional very high waves or seiches.

AIR PRESSURE IN THE SAND

The escape of air from dry beaches just as they are first covered by water at high tide was described by Cornish (1912) and by Kindle (1926). However, even after the upper part of a beach has been wet by previous waves, more air may escape when another wave washes up the beach slope, provided several minutes elapse between waves. The escape of air is shown by the presence of streams of bubbles rising through the water, and by the continued formation of small sand holes shortly after the water has run back downslope. On the seaward sloping portion of a beach the escape of air caused by a single wave lasts only a minute or two. However, on the backslope, where water may collect in shallow pools at high tide, air has been observed to escape for about two hours. The pressure of the escaping air is sometimes sufficient to form a fountain reaching about five centimeters above the surface of these pools.

A simple means of measuring the air pressure was made by attaching an inverted glass funnel to an open U-tube manometer half filled with distilled water colored by potassium permanganate. The large end of the funnel was pushed about 5 millimeters into the sand over a hole through which air was escaping and the pressure of the air determined by measuring the difference in height of the colored water in each side of the U-tube.

About a hundred measurements were made during successive waves at high tide on a fine sand beach sloping 7 degrees at a spot a few meters from the cavernous sand illustrated in plate 3, figure 2. The waves were 1 to 10 centimeters deep at the site of the measurements. A composite curve showing the pressure variation with time is illustrated in figure 2. Some of the individual measurements showed higher pressures, and others lower pressures but the composite curve is probably typical. It will be noted that immediately after the sand was covered by a wave the pressure of air escaping from a sand hole rose abruptly and reached a

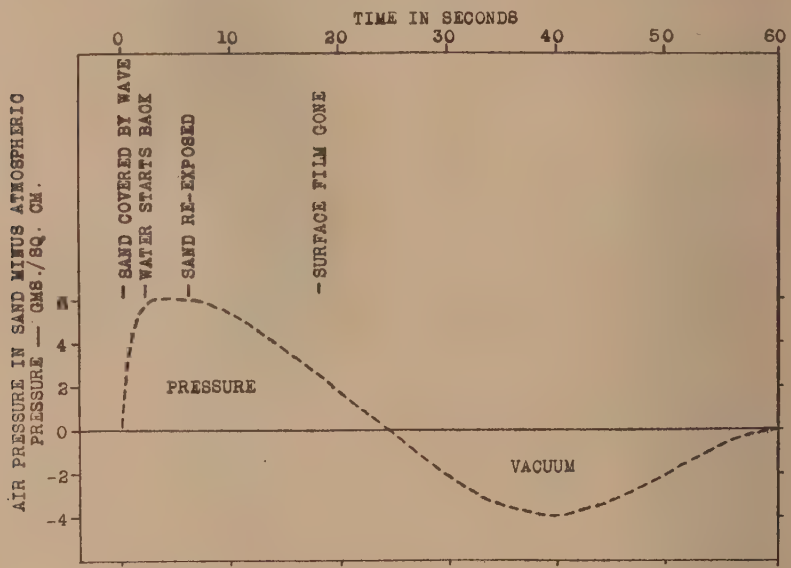

FIG. 2.—Variation of air pressure in fine sand following the wash of a wave up the beach slope.

maximum about 4 seconds after the wave covered the sand. These maximum pressures depended more on the time interval between waves than on the wave height. A typical maximum pressure was 6 grams per square centimeter, or about 1.4 ounces per square inch. At about 6 seconds the water had re-exposed the sand except for the presence of a thin surface film which disappeared at about 18 seconds. The pressure dropped roughly linearly during the period between 6 and 25 seconds after the wave covered the beach, following which it was again zero (equal to atmospheric pressure). However, after reaching zero, the pressure in the funnel continued to drop, forming a slight vacuum until about 40 seconds when the pressure was about 4 grams per square centimeter below atmospheric pressure. The pressure difference then gradually decreased so that at about 60 seconds the pressure within the tunnel equalled atmospheric pressure. In the area within a few centimeters of the site of the measurements, bubbles rose through the sand between 2 and 6 seconds, forming a few very small cratered holes. From 6 to 25 seconds numerous sharp-edged holes and a few small sand domes formed.

On the nearby backslope of the beach a pool of water collected as the waves washed over the highest part of the beach at high tide. Air escaped from cratered holes within the pool for about 20 minutes. The maximum pressure measured was 23 grams per square centimeter, or 5.2 ounces per square inch.

Similar measurements were made during successive waves on a very coarse sand beach sloping 12 degrees and in which only a few sand holes were present. A typical maximum pressure was 10 grams per square centimeter, and a typical vacuum only 2 grams per square centimeter. The entire period of pressure variation was about 10 seconds.

ORIGIN

Sand holes, sand domes, and cavernous sand are usually found in the same general environment, on the highest part of a beach reached by high tide. On most beaches all three features are closely associated. None are common in very fine or very coarse sand, but all occur in sand of intermediate grain size. Only air is found in the sand holes and their feeder channels, in sand domes, and in the cavities of cavernous sand.

It is suggested that as a wave recedes, the sand becomes partly drained and the spaces between sand grains partly filled with air. As the next wave rapidly advances over the beach slope, the interstitial water also works up-dip, but more slowly. As a result, when the wave reaches its maximum height on the beach, the front of the slowly moving mass of interstitial water may be left several feet behind. Part of the water of the wave begins soaking into the beach sand. Air already in the sand pore spaces may then be trapped between the water soaking downward near the point of farthest advance of the wave and the interstitial water working back up-dip. This air may be forced out of the sand, developing sand holes en route. Palmer (1928) proposed a somewhat similar origin but only for beach sands consisting of alternating coarse and fine grained laminae. Actually, sand holes may form in unlaminated sand.

Where the beach is well laminated, as described by Thompson (1937), the water drains down-dip more rapidly in the coarser than in the finer laminae and is replaced by air as the wave retreats. When the next wave advances, the air is driven along the coarser layers and collects in pockets. If the overlying layer of wet fine sand is air tight, it may be arched upward and a sand dome is formed as described also by Palmer (1928) and by Johnson (1938). Domes may also be formed by the washing of a plug of sand into a sand hole through which air is escaping (Emery, 1944).

The presence of air in cavernous sand and the general similarity of environment and association of cavernous sand and the sand domes and sand holes suggests a

similar origin. The origin of cavernous sand by trapping of air between interstitial water advancing up-dip and water soaking downward through the sand was in fact, suggested by Kindle (1936). Trefethen (1941) objected to this origin but offered only the suggestions that soft or cavernous sand is the result of open packing developed by the lifting effect of escaping air, or by reworking by wind and organisms. A careful search for organisms, such as sand hoppers, which might be capable of forming the cavities at Mission Bay failed to reveal their presence. Also, cavernous sand was found at several places which were well protected from the wind. The entrapment of air in the sand, moreover, seems to be the only process capable of forming cavities having a diameter more than 30 times that of the sand grains forming the cavity walls.

A further indication of the relationship between the features and the entrapment of air is shown by the fact that the features are rare or absent in very coarse or very fine-grained sand. Very coarse sand has such large intergranular spaces, and consequent high permeability, that the air can escape so easily that sand domes and cavities cannot be formed. The very fine-grained sand beaches such as those near Galveston, Texas, do not permit rapid drainage of interstitial water and, as a result, air is not admitted and thus cannot be trapped.

Drainage of the upper part of the beach can take place only when the water table is low, or during low tide. The most complete drainage and, therefore, the most favorable conditions for formation of cavernous sand should exist at the bi-weekly periods of spring tides when the lowest tides and the largest tide ranges occur. The neap tides, correspondingly, should offer the least favorable conditions. Ranges between low tides and high tides of 2.6 meters at the time of spring tides and 1.3 meters at neap tides are typical. Measurements of the thickness of cavernous sand at the site of plate 3, figure 2 were made daily throughout one bi-weekly tidal cycle and at irregular intervals during 4 other bi-weekly cycles. Thickness of the layer was taken as the maximum depth of footprints. It was found that the thickness averaged about 15 centimeters for about 5 days beginning with the day of spring tide. Afterward, it gradually decreased to about 5 centimeters until the next spring tide, when it increased rather suddenly to about 15 centimeters. The sequence was repeated during the next bi-weekly tidal cycle. Similarly, a few measurements near the site of plate 2 showed a range of 5 centimeters during one or two days after spring tide to less than 1 centimeter during the period between neap tide and the following spring tide. The fact that on neither beach was there an increase in thickness of the layer of cavernous sand during the several days preceding spring tide may be due to the presence of another factor: the prevalence of deposition or erosion of sand during intermediate parts of the bi-weekly tidal cycle, as discussed by Shepard and La-Fond (1940).

GEOLOGICAL SIGNIFICANCE

Features developed by air entrapped in the sand have several possible geological applications:

1. Sand holes and sand domes can serve as criteria of the true order of deposition for steeply inclined or vertical beds of sandstone. The sand holes are likely to be filled by sand and may not be easily recognizable. However, similar holes have been discovered in the Cambrian Tapeats sandstone of the Grand Canyon (E. D. McKee—personal communication). Truncated sand domes formed in laminated sand should be even more easily recognized, either in sections across the bedding (pl. 2, fig. 1) or parallel to the bedding (pl. 2, fig. 2). They are probably also more likely to be preserved than swash marks, which have been reported in ancient sandstones (Clarke, 1918), A similar geological role

as a criterion of the order of deposition has been assigned ripple marks (Twenhofel, 1932, pp. 665, 666) but on most beaches sand domes are far more abundant.

2. The greater abundance of the sand holes, sand dunes, and cavernous sand near the upper part of marine beaches is probably the result of the more complete drainage during low tide with consequent entrance of air which later becomes trapped as the tide again rises as discussed above. In lakes or other bodies of water having no tide and only small waves, drainage of beaches is less complete and the features should not be so abundant. Accordingly, an ancient sandstone containing an abundance of these features on most of the laminae was probably deposited as a marine beach. If the features are rare, or present on only a few laminae, they could have been formed during a storm, a seich, or a heavy rainfall on a lacustrine beach. The features are probably extremely rare in dune sands.

3. Kindle (1936) suggested that the cavernous sands may become layers containing abundant concretions developed because of the free circulation of ground water. Concretions, however, probably must form before the cavernous layer is deeply buried, because of the likelihood of compaction. This ease of compaction also renders unlikely his suggestion that the cavernous sands may become good oil and gas reservoirs.

4. Tracks made by an animal walking over cavernous sand may be very deep even though the animal be of relatively little weight. Moreover, it is even possible that tracks formed in ancient cavernous sands may later be shown as raised areas, because the original track depression is likely to be filled by non-cavernous sand which will be less compacted than surrounding cavernous sand by the weight of overlying beds.

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15.

ankton of the Bermuda Oceanographic Expeditions. XI. Bathypelagic emerteans of the Bermuda Area and Other Parts of the North and South Atlantic Oceans, with Evidence as to Their Means of Dispersal.[1]

WESLEY R. COE.

Osborn Zoological Laboratory, Yale University, and the Scripps Institution of Oceanography, University of California.[2]

(Plates I and II; Text-figures 1-26).

[This is one of a series of papers dealing th the plankton collections of the Bermuda eanographic Expeditions of the Department Tropical Research, New York Zoological ciety, made under the direction of Dr. Wil- m Beebe during the years 1929, 1930 and 31. For complete trawling data, refer to ebe, *Zoologica*, Vol. 13, Nos. 1 (1931), 2 931) and 3 (1932).]

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37. *Balaenanemertes grandis* Brinkmann 164
38. *Balaenanemertes hjorti* Brinkmann 164
39. *Balaenanemertes lata* Brinkmann 164
40. *Balaenanemertes lobata* (Joubin) 164
41. *Balaenanemertes minor* Coe 165
42. (?) *Balaenanemertes musculocaudata* Brinkmann 165
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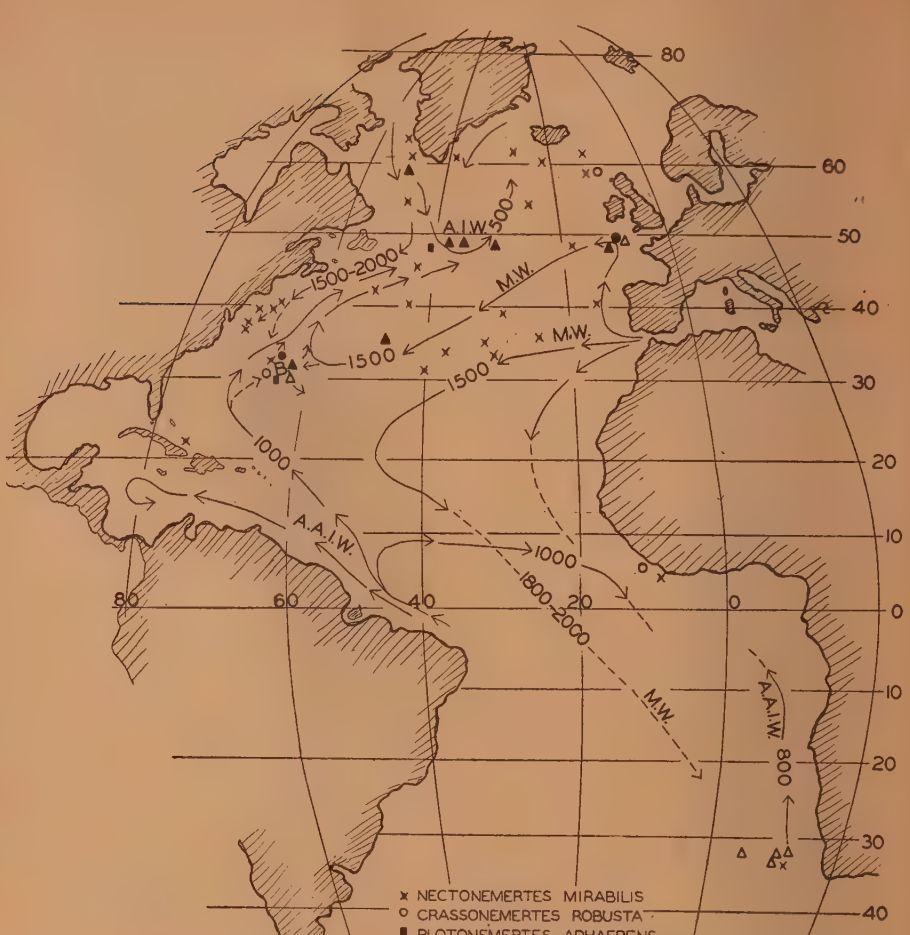
[1] Contribution No. 716, Department of Tropical Research, New York Zoological Society.

[2] Contributions from the Scripps Institution of Oceanography, New Series No. 261.

INTRODUCTION.

Previous reports (Coe, 1935, 1936) on the bathypelagic nemerteans taken in the years 1929, 1930 and 1931 by the Bermuda Oceanographic Expeditions of the New York Zoological Society under the direction of Dr. William Beebe contained an account of the 79 specimens which were available for study at that time. These included 12 species belonging to 10 genera, of which 6 species and one genus were new to science. The collections also contained material which made possible the description of both sexes in 4 species of which only one of the two sexes had been previously described.

The 1936 report was illustrated by photo-



TEXT-FIG. 1. Correlation of the distribution, insofar as at present known, of six of the species of bathypelagic nemerteans found in the Bermuda area with the approximate directions of flow of the water masses which they inhabit. Numerals indicate the approximate distances from the surface at which the intermediate water masses are flowing. Broken lines are used for less well authenticated currents. Abbreviations indicate: **A.I.W.**, arctic intermediate water; **A.A.I.W.**, antarctic intermediate water; **M.W.**, Mediterranean water; **B**, Bermuda area. (Modified from Sverdrup, Johnson and Fleming, "The Oceans," 1942, with additional data through the courtesy of Dr. Sverdrup).

graphs of preserved specimens of each species, as well as by drawings showing the internal anatomy. Descriptions were given of such of the morphological details of each species as had not been previously reported. Information was also included as to the depth at which each specimen was found, together with the geographical distribution of the species as known up to that time.

The present, supplementary, report based upon additional material which w collected at the same time as that includ in the earlier reports and which has sin become available for study. It includes d scriptions and figures of two new specie *Mononemertes scarlata* and *Parabalaen nemertes nigra*, and the diagnosis of o new genus, *Calonemertes*.

Distribution.

e collections were all made by Dr. Wil-
Beebe in a relatively minute portion
deep subtropical Atlantic Ocean. This
n was a circular column of water
miles in diameter, with its center lo-
at 32°12′ N. Lat., 64°36′ W. Long.,
nine miles southeast of Nonsuch
l, Bermuda. The nets were drawn hor-
lly across this area so as to collect
es simultaneously at 200-meter inter-
from depths of about 1,000 to 2,000
s. During the years 1929, 1930 and
a total of 1,042 nets one meter in di-
r were drawn at these depths in all
ions across this eight-mile cylinder of

ause of the fact that the nets were
to the surface while still open, there
ays a possibility that any particular
dual may have actually been caught
igher level than that at which the net
drawn horizontally. However, if the
species was not also caught in any of
ets drawn horizontally at the higher
there is small probability that the
s lives there.

e nets were drawn horizontally for
ls of about four hours after the bot-
et had reached the depth of about 2,000
s and then drawn vertically to the
ce. It must be remembered, however,
he nets did not enter exactly the same
in successive years nor even in suc-
e days, for the ocean currents are
ntly transporting the water from one
n of the ocean to another. Through
gency of these currents the constituent
tonic fauna of any particular water
is being slowly but continually distri-
to other geographical areas.

ause of this continuous flow of the
masses the actual volume of water
gh which the nets passed during the
summers must have been vastly great-
an that of an equal cylinder of sta-
y water. The water masses at the
y mentioned during the summer of
ear were doubtless far distant the
ing summer and the bathypelagic
collected on any particular date must
arrived at that locality just in time
caught by the nets. We may there-
ssume that the sexually mature worms
ined in the collections studied may
originated as young individuals some
distant and that their offspring may
some other part of the ocean not too
way.

must not be assumed, however, that
water masses with their suspended
s are flowing like a river in a single
ion, for oceanographers have deter-
l that the generally onward movement of the water is the resultant of innumerable streams with side eddies flowing in all directions. Hence it is not inconceivable that an individual which may have once narrowly escaped the net in the Bermuda area may nevertheless have been caught in the same net at the same place some weeks or months later, after having made a circuit outside the area in the meantime.

The water layer which forms the habitat of most species of bathypelagic nemerteans lies at a depth of 1,200 to 2,000 or more meters in the Bermuda area. The temperature averages about 4° Centigrade, being 5.3° at 1,200 meters and 3.5° at 2,000 meters. The salinity is from 34.99 to 35.08 parts per thousand. Water masses with these characteristics are continuous throughout the North Atlantic, being at a higher level in the north and deeper in the south. Because of the low temperatures at these depths, the viscosity of the water is sufficient to enable the nemerteans with their horizontally flattened, gelatinous bodies to support themselves with a minimum of muscular effort.

The region off the coast of Bermuda where the collections were made is particularly favorable for a wide variety of bathypelagic animals because of the admixture of ocean waters derived from several widely separated sources (Sverdrup, Johnson and Fleming, 1942)[3]. Such evidence as is at present available indicates that the intermediate ocean water which the nemerteans inhabit, at depths of 1,200 to 2,000 meters, has a large component of water of subantarctic origin (Text-fig. 1). This moves in a generally northerly direction at a rate which has been estimated as at least one-half centimeter per second or perhaps 400 meters per day. That would indicate a movement approaching one mile in four days. If it could be assumed that such a flow is continuous and at a rate of approximately 90 miles per year, it would require a period of only about 40 to 50 years to bring a population of these worms from the South Atlantic to the Bermuda area. From the Bermuda area the population may be carried farther to the north or deflected toward the east and thence to the middle Atlantic. Other currents may return the population southward and thence to the South Atlantic.

A second source of the intermediate water off Bermuda is a current originating in the subarctic region of the Atlantic (Text-fig. 1). This flow is less well differentiated than that from the South Atlantic but it doubtless brings from higher levels

[3] For additional data relative to the movements of these water masses of intermediate depths, the writer is indebted to Dr. H. U. Sverdrup, Director of the Scripps Institution of Oceanography.

in the north, water which sinks to greater depths off Bermuda. Consequently it need occasion no surprise to find that *Nectonemertes mirabilis,* which may be found only 500 meters from the surface in the seas near Greenland, lives at depths of 1,300 to 1,800 meters or lower in the Bermuda area. After mixing with the South Atlantic water the flow may return northward or be diverted toward the eastern North Atlantic.

A third source of water which may mingle with the flows from north and south already mentioned is the Mediterranean outflow (Text-fig. 1). Although there are no bathypelagic nemerteans in the Mediterranean Sea, the populations in the eastern North Atlantic may be brought into the currents of mixed water as they flow from east to west through the central North Atlantic.

Hence, it may be expected that populations from any or all of these and perhaps from other sources may be found drifting past the Bermuda area in one direction or another whenever a net is lowered to the depth at which each species finds the conditions for survival and reproduction most favorable. But the populations encountered may differ from month to month or even from day to day, although one species, *Nectonemertes mirabilis,* appears to be present at all times. This species is found not only in the Bermuda area but also throughout the North Atlantic and it has also been reported from the South Atlantic. (Text-fig. 1). Hence it is obvious that no matter what may be the direction of the flow at the time of the collection or from whence the water may have come, that species will always be present, either in the net or in the vicinity.

Another species, *Plotonemertes adhaerens,* seems to find the mixed waters of the Bermuda area particularly favorable for reproduction, since a total of 35 representatives of this species has been obtained in that area, while only a single specimen has as yet been found in all the rest of the oceans. It is possible however that the nets used elsewhere were not lowered to the appropriate depth, for this species lives near the lowest limits reached by any of the nets in the Bermuda area. The single specimen known from the middle North Atlantic was likewise taken in the lowest net. Consequently the lowest limit of the population has not been determined.

The fact that in several cases only a single specimen of a species was obtained in a total of more than 600 nets lowered to the depth at which that specimen was found and drawn there horizontally for four hours indicates how sparse must have been the population at those levels and at those times. It may have been only a lucky chance that brought the net to the ex position occupied at that moment by nemertean. Or perhaps by an unluc chance the nets barely missed catch other individuals. At lower levels or other times it is quite conceivable that results might have been different.

With a drifting population which may carried in various directions throughout vast expanse of the North and South lantic oceans, the chances of finding w a one-meter net even a single representat of a species composed of millions of dividuals must be very small. It seems hi ly probable, moreover, that portions of population may be carried to levels or regions unfavorable for survival, perh too near the surface or to too great dept These nemerteans, however, in spite their feeble musculatures, have some pacity for resisting such currents as mi tend to carry them above or below the le of their natural habitats. Individuals *Nectonemertes mirabilis* and *Pelagonem tes rollestoni* have been observed to sw with considerable vigor for a brief per in spite of the great changes in tempe ture and pressure which they must h endured while being brought from th natural depths to the surface.

The influence of eddies and return currents may be of great importance in localization of populations and it is not probable that there are some regions wh a species could remain within a more or l closely circumscribed area indefinite From such an endemic area representati of the species might be carried to dist parts of the ocean, reproducing success generations on the way.

If the direction and extent of these d ocean currents were fully known it wo be possible to predict the probable dist bution of such of the bathypelagic spec as inhabit particular water masses. A conversely the distribution of the vari species of these nemerteans will doubtl furnish reliable clues as to the extent the movement of water masses hav physical and chemical characteristics which they are adapted.

If the oceanographers had not alre obtained satisfactory evidence of the tra fer of South Atlantic water northw across the equator, the known distribut of *Nectonemertes mirabilis* and other s cies would indicate that the water m which they inhabit, actually does m across the equator (Text-fig. 1). But si the place of origin of that species is known there would be no evidence as whether the water flows north or south

With the information now available to the circulation of the Atlantic wa

sses, it is not surprising to find that the cies mentioned appears to be distributed the way from the South Atlantic to the s east and west of southern Greenland. nas already been found in the South At- tic west of South Africa, in the equa- ial Atlantic, near the West Indies, off the tern coast of North America, through width of the North Atlantic to near the st of Spain and northward to the lati- e of southern Greenland. This indicates ange of nearly 100 degrees of latitude, m 34° S. Lat. to 64° N. Lat. (Text-fig. 1). *Protopelagonemertes hubrechti* has like- e been found in the South Atlantic west South Africa, in the Bermuda area and the eastern North Atlantic southwest reland. *Crassonemertes robusta* has been orted from the equatorial Atlantic (7° Lat.) near the coast of Africa, in the rmuda area and northwest of Great tain (58° N. Lat.). These are the only cies that have as yet been found both the tropical or South Atlantic and in the rmuda area, but it must be remembered t up to the present time relatively few nples of the bathypelagic fauna of the antic between 30° S. Lat. and 30° N. Lat. e been obtained.

Another species with a wide geographical ge is *Pelagonemertes rollestoni*, although nas not been found in the Bermuda area in any part of the North Atlantic north 7° N. Lat. This species occurs through- the entire width of the South Atlantic l it has also been taken in the northern t of the Indian Ocean, as well as far th of Australia. This range covers near- 180 degrees of longitude and about 55 rees of latitude. The depth at which the cies lives is definitely known, for it has n taken in closing nets at depths between to 1,600 meters (Wheeler, 1934). The at differences in surface temperatures hese far distant regions presumably have le influence on the natural habitat of these rms so far beneath the surface. The gen- l circulation of the water masses at these ths in the southern oceans appears to be h as to aid the distribution of the species m east to west. A northern branch of s circumpolar flow seems to have carried species northward along the west coast Africa to a region beyond the equator. ext-fig. 1).

Only two individuals of *Chuniella lanceo-* are known at present. One of these was nd in the Bermuda area and the other the North Atlantic southwest of Ireland. e former specimen was caught at a th of about 1,600 meters and the latter 1,000 meters.

f the collected specimens have been cor- tly identified, another species with a wide geographical distribution is *Dinonemertes investigatoris*, for the type specimen came from the northern Indian Ocean, while two other representatives were taken in the central North Atlantic at Lat. 34° and 48° N. Even if it be assumed that a single population of this species extends at the present time throughout the range indicated, such a population would find essentially uniform conditions in its normal habitat at depths between 1,000 and 2,000 meters in all parts of this wide expanse of oceans. *Nectonemertes minima* has been taken at various localities in the eastern Atlantic oceans, from a point northwest of Ireland, across the equator to near the Cape of Good Hope. This represents a distance of 92 degrees of latitude (57° N. to 35° S.).

As a consequence of this wide circulation of the ocean waters it seems quite possible that all the species of bathypelagic nemerteans that have been found in any part of the North or South Atlantic may at times drift through the Bermuda area. This must likewise be the case with such of the other populations of the bathypelagic faunas as are adapted for drifting along with the currents. Nevertheless Beebe (1937) found that certain populations of fishes in the Bermuda area remained nearly stable for the three successive years when the collections were made. Because of their greater motility, however, the fishes are presumably able to remain in any suitable locality regardless of the movements of the water.

It seems highly improbable, however, that the populations are distributed uniformly over the wide expanse of the oceans between the two or more localities where their representatives have been found. Nor should a species be thought to be restricted to a closely limited area simply because it has been taken at only a single locality. It seems more probable that the populations of one or more species are associated in more or less widely dispersed groups which drift about in the currents or eddies generation after generation as long as the regions to which they are carried offer favorable conditions for existence.

Up to the present time 34 species, representing 21 genera, have been reported from the Atlantic oceans outside the Bermuda area. Only 6 of these have as yet been found within that area and 8 species have been collected in the Bermuda area that have not yet been discovered elsewhere.

This report brings the total number of species reported from the Atlantic oceans to 42, assigned to 10 families and 22 genera, including 14 species, belonging to 12 genera, from the Bermuda area. In addition to these, 15 other species have been collected in the Pacific and Indian oceans, bringing

to 57 the total number of species of bathypelagic nemerteans at present described. Further exploration of the oceans will presumably greatly increase this number, perhaps several fold.

The finding of so many more species in the North Atlantic than in the other oceans should not be considered as valid evidence that they are more abundantly represented in the North Atlantic than elsewhere but that this is merely the result of more intensive exploration. Only 6 species have thus far been found in the Indian Ocean, of which 2 occur also in the Atlantic. None of the 11 species collected in the Pacific Ocean has been found in the Atlantic; the deep waters from one of these two great ocean basins can not circulate directly into the other so far north as those regions in which collections have been made.

In order to facilitate the identification of these species, revised analytical keys are included for all the families of bathypelagic nemerteans and for such genera and species as are known to live in the Atlantic oceans. Most of the species are illustrated by Text-figures and anatomical details of the two new species are shown in Plates I and II.

The distribution of each of the 57 species, in so far as known at the present time, is shown in the following lists.

Distribution of Species.

Distribution of species known to inhabit the North or South Atlantic oceans, or both. Reported from the Bermuda area (B); from other parts of the North Atlantic (N); from the South Atlantic (S); from the Indian Ocean (I).

Family Protopelagonemertidae.

1. *Protopelagonemertes beebei.* (B)
2. ——— *hubrechti.* (B,N,S)
3. *Calonemertes hardyi.* (S)
4. *Plotonemertes adhaerens.* (B,N)
5. ——— *aurantiaca.* (B)
6. *Pendonemertes levensini.* (N)

Family Planktonemertidae.

7. *Planktonemertes vanhoeffeni.* (S)
8. *Mononemertes sargassicola.* (N)
9. ——— *scarlata.* (B)
10. *Crassonemertes robusta.* (B,N)
11. ——— *rhomboidalis.* (N)
12. *Pachynemertes obesa.* (B)

Family Buergeriellidae.

13. *Buergeriella notabilis.* (N)

Family Dinonemertidae.

14. *Paradinonemertes drygalskii.* (N)
15. ——— *wheeleri.* (B)
16. *Dinonemertes alberti.* (N)
17. ———*grimaldii.* (N)
18. ——— *investigatoris.* (I,N)
19. *Planonemertes labiata.* (B)

Family Phallonemertidae.

20. *Phallonemertes murrayi.* (B,N)

Family Chuniellidae.

21. *Chuniella agassizii.* (N)
22. ——— *elongata.* (N)
23. ——— *lanceolata.* (B,N)

Family Nectonemertidae.

24. *Nectonemertes minima.* (N,S)
25. ——— *mirabilis.* (B,N,S)
26. ——— *primitiva.* (N,S)

Family Armaueriidae.

27. *Armaueria rubra.* (N)

Family Pelagonemertidae.

28. *Natonemertes acutocaudata.* (N)
29. *Gelanemertes richardi* (N)
30. *Pelagonemertes rollestoni.* (N,S,I)
31. *Parabalaenanemertes fusca.* (N)
32. ——— *nigra.* (B)
33. ——— *zonata.* (N)
34. *Probalaenanemertes irenae.* (S)
35. ——— *wijnhoffi.* (N)

Family Balaenanemertidae.

36. *Balaenanemertes chavesi.* (N)
37. ——— *grandis.* (N)
38. ——— *hjorti.* (N)
39. ——— *lata.* (N)
40. ——— *lobata.* (N)
41. ——— *minor.* (B)
42. (?) ——— *musculocaudata* (=*lobata*) (N)

Distribution of species which are not present known to occur in either the Nor or South Atlantic Ocean.

Family Planktonemertidae.

Planktonemertes agassizii Woodwor Pacific Ocean.

Mergonemertes woodworthii Bürger, dian Ocean.

Neuronemertes aurantiaca Coe, Paci Ocean.

Family Dinonemertidae.

Dinonemertes mollis Coe, Pacific Ocea

Planonemertes lobata Coe, Pacific Oce

Family Chuniellidae.

Chuniella pelagica Bürger, Indian Oce

Family Nectonemertidae.

Nectonemertes japonica Foshay, Paci Ocean.

——— *pelagica* Cravens and Heath, cific Ocean.

Family Armaueriidae.

Proarmaueria pellucida Coe, Pacific Oce

Cuneonemertes gracilis Coe, Paci Ocean.

Family Pelagonemertidae.

Pelagonemertes joubini Coe, Pacific Ocean.
——— *moseleyi* Bürger, Pacific Ocean.
——— *brinkmanni* Coe, Pacific Ocean.
Nannonemertes indica Wheeler, Indian Ocean.

Family Balaenanemertidae.

Balaenanemertes chuni Bürger, Indian Ocean.

KEY TO FAMILIES.

1. Anterior end of body without tentacles in either sex 2
1. Anterior end of body with pair of tentacles in one or both sexes..... 9
2. Dorsal blood vessel extends entire length of body 3
2. Dorsal vessel ends blindly in rhynchocoel a short distance posterior to brain .....Pelagonemertidae
3. Posterior end of body narrow, not differentiated into caudal fin..... 4
3. Posterior end of body broad and flat, usually terminating in flattened caudal fin 6
4. Musculature of proboscis sheath of interlacing circular and longitudinal fibers .....Protopelagonemertidae
4. Musculature of proboscis sheath of separate circular and longitudinal layers 5
5. Intestinal diverticula numerous, with few branches and without distinct ventral branch .....Chuniellidae
5. Intestinal diverticula few, divided repeatedly into numerous slender branches .....Buegeriellidae
6. Dorsal vessel does not enter rynchocoel Armaueriidae
6. Dorsal vessel enters rhynchocoel..... 7
7. Intestinal diverticula with both dorsal and ventral branches, the latter extending laterally beneath the nerve cords .....Planktonemertidae
7. Intestinal diverticula without distinct ventral branches 8
8. Body broad and flat; spermaries without external phalli....Dinonemertidae
8. Body slender; spermaries with external phalli .....Phallonemertidae
9. Anterior portion of body with pair of lateral tentacles in adult males only; dorsal vessel extends entire length of body .....Nectonemertidae
9. Head with pair of small lateral tentacles in both sexes; dorsal vessel rudimentary, ending blindly in rhynchocoel .....Balaenanemertidae

FAMILY
PROTOPELAGONEMERTIDAE.

Key to Genera.

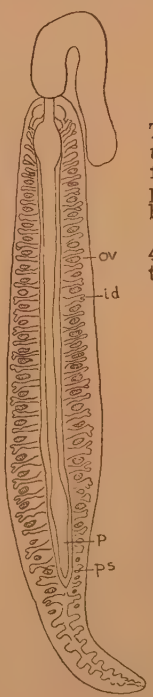
1. Mouth and proboscis opening united; proboscis sheath extends to posterior end of body.....*Protopelagonemertes*
1. Mouth and proboscis opening separate 2
2. Proboscis sheath about half as long as body; nerve-cord muscles present; glandular adhesive organs absent *Pendonemertes*
2. Proboscis sheath at least three-fourths as long as body 3
3. Proboscis sheath three-fourths as long as body; nerve-cord muscles absent; ventral surface of body with pair of convoluted glandular organs, more highly specialized in the male *Plotonemertes*
3. Proboscis sheath extends to posterior end of body; convoluted glandular organs absent .....*Calonemertes*

Genus ***Protopelagonemertes*** Brinkmann.

1. ***Protopelagonemertes beebei*** Coe, 1936.

Text-figure 2.

The only representative of this species as yet known was taken in the Bermuda area at a depth of about 1,646 meters. This was a mature female measuring 24 mm. in length and 7 mm. in width. The color in life



TEXT-FIG. 2. *Protopelagonemertes beebei*. Outline of body of female with partially everted proboscis, showing extent of proboscis sheath **(ps)** and proboscis **(p)**, 30 pairs of ovaries **(ov)** and 40 pairs of lobed intestinal diverticula **(id)**. (After Coe).

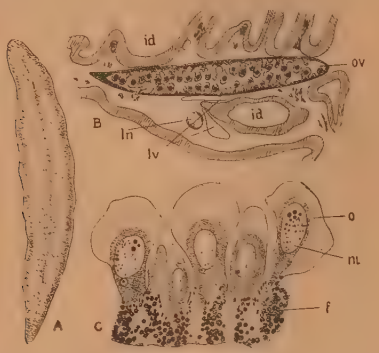
was orange yellow, with paler lateral margins.

2. ***Protopelagonemertes hubrechti*** Brinkmann.

Bathynectes hubrechti Brinkmann, 1912, 1917, 1917a; *Protopelagonemertes hubrechti* Brinkmann, 1917a Nachtrag; Coe, 1926, 1935, 1936; *Bathynemertes hubrechti* Wheeler, 1934.

Text-figure 3.

Three representatives of this species were contained in the collection from the Bermuda area reported previously (Coe, 1936). All of these, as well as the type specimen, were females. One additional female measuring 37 mm. long and 6 to 8 mm. wide was found in the supplementary collection. No male has as yet been discovered.



TEXT-FIG. 3. *Protopelagonemertes hubrechti.* **A**, typical shape of body; **B**, ovary **(ov)**; **C**, portion of ovary showing relation of ova **(o)** to follicle cells **(f)**; other letters indicate: **id**, intestinal diverticula; **ln**, lateral nerve; **lv**, lateral blood vessel; **nu**, nucleus. (After Brinkmann).

The depths at which the Bermuda specimens were found ranged from 1,400 to 1,800 meters but inasmuch as one of the 4 specimens was found at the level reached by the lowest net, it is probable that the habitat in the Bermuda area may extend to still greater depths.

The colors in life are described as red, scarlet or orange.

Geographical distribution. In addition to the Bermuda area the species has been reported from the eastern North Atlantic southwest of Ireland, at a depth of 2,000 meters, and from the eastern South Atlantic west of the southern point of Africa at depths of 1,000 meters or less to 2,500 meters or less. One of the specimens from the South Atlantic is known to have been taken at a depth between 1,310 and 1,410 meters.

Genus ***Calonemertes,*** new genus.

Species of this genus resemble those of *Protopelagonemertes* in general appearance but differ in having separate openings for mouth and rhynchodeum. Because of these characteristics this new genus must be adopted for the species described by Wheeler (1934) as *Bathynemertes hardyi.*

Body narrowed at both ends, rounded and moderately slender, without indication of lateral or caudal fins; mouth separate from rhynchodeal opening, provided with frilled lips when opened; esophagus absent; proboscis sheath extends entire length of body, musculature of interlaced longitudinal and circular fibers.

3. ***Calonemertes hardyi*** (Wheeler).

Bathynemertes hardyi Wheeler, 1934.

Text-figure 4.

A single female represents the type of this species. It is one of the largest of all the bathypelagic nemerteans, the type specimen measuring 110 mm. in length, 25 mm. in width and 13 mm. in thickness. This specimen agrees in many respects with the large female described and figured by Coe (1936) as an unusually large individual of *P. hubrechti* but differs in having separate openings for mouth and rhynchodeum. The body is narrow, rounded and without lateral or caudal fins.

The proboscis sheath extends the entire length of the body and its muscular wall is composed of interlacing longitudinal and circular fibers. The color of the body in life was scarlet with irregular patches of black pigment (Text-fig. 4).

This species is known only from the type specimen which was obtained in an open net lowered to a depth of 1,000 meters and

TEXT-FIG. 4. *Calonemertes hardyi.* Outlines of body from ventral **(A)** and dorsal **(B)** surfaces, showing the irregular patches of black pigment. (After Wheeler).

rawn to the surface. The locality was in ne eastern South Atlantic west of the Cape f Good Hope.

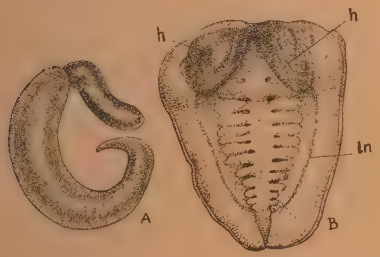
Genus ***Plotonemertes*** Brinkmann.

. ***Plotonemertes adhaerens*** Brinkmann, 1917.

Text-figure 5.

. adhaerens Brinkmann, 1917, 1917a; Coe, 1926, 1935, 1936.

In addition to the 27 specimens previous- reported from the Bermuda area (Coe, 935, 1936), the present collections con- ained 8 individuals, representing both exes. These varied in length from 8 to 16 m. One specimen was taken at a depth f about 1,100 m., 5 from a depth of 1,500 . and two from 1,800 m.



TEXT-FIG. 5. *Plotonemertes adhaerens.* **A**, type pecimen with everted proboscis; **B**, ventral sur- ace of posterior end of body, showing pair of landular organs **(h)** and lateral nerves **(ln)**. After Brinkmann).

The 27 specimens included in the earlier eport (Coe, 1936) came from depths of ,300 to 1,830 m. Since none of the nets was owered below 1,830 m., it seems possible hat the species may also inhabit somewhat reater depths in that region. The type pecimen came from about 2,000 m. The umber of individuals caught increases ith depth from 1,100 to 1,600 m. and then iminishes with increasing depths to 2,000 . Hence the optimum depth of the species n the Bermuda area would seem to be bout 1,600 m.

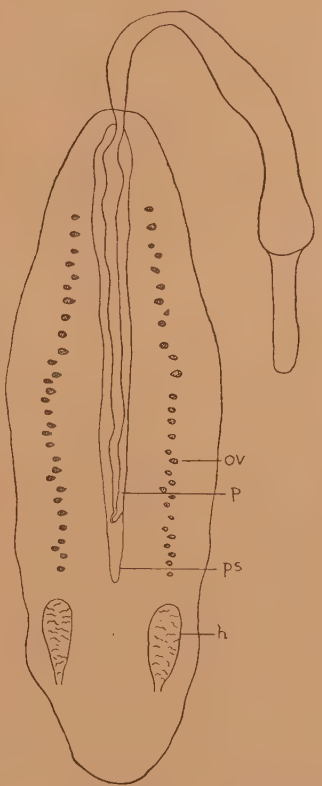
With the exception of *Nectonemertes mi- abilis*, this was the most abundant bathy- elagic nemertean in the Bermuda area be- ween the depths of 1,100 and 1,830 m. at he times when these collections were made. t was not taken in any of the nets drawn t higher levels. Only a single specimen has een found in any other part of the ocean nd this was collected near the middle of he North Atlantic (47°34′ N. Lat., 43°11′ V. Long.).

Mature individuals of both sexes vary rom 12 to 30 mm. in length and 2 to 9 mm. n width. The colors in life are reported as ink, pinkish-orange, orange and red. Detailed descriptions and figures of the organ systems may be found in the papers by Brinkmann (1917a) and Coe (1936).

5. ***Plotonemertes aurantiaca*** Coe, 1936.

Text-figure 6.

Only the type specimen of this species is known at present. This was a mature female 40 mm. in length, 11 mm. in width and 5 to 7 mm. in thickness. The color in life was bright orange, with yellow margins, caudal fin and proboscis. It was taken in the Bermuda area at a depth of about 1,463 meters.



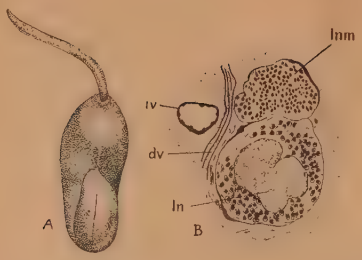
TEXT-FIG. 6. *Plotonemertes aurantiaca*, ventral surface of body of female, showing pair of glandular organs **(h)**, ovaries **(ov)**, extent of proboscis sheath **(ps)**, and attachment of proboscis **(p)**. (After Coe).

Genus ***Pendonemertes*** Brinkmann.

6. ***Pendonemertes levensini*** Brinkmann, 1917.
P. levensini Coe, 1926.

Text-figure 7.

The three known representatives of this species were taken in the eastern North Atlantic (Lat. 35° to 50° N., Long. 7° to



TEXT-FIG. 7. *Pendonemertes levensini.* **A**, female from ventral surface; **B**, transverse section of lateral nerve cord **(ln)** with accompanying nerve-cord muscle **(lnm)**, lateral blood vessel **(lv)** and dorsoventral muscles **(dv)**. (After Brinkmann).

11° W.) at depths of 1,000 to 2,260 meters. All were females.

FAMILY PLANKTONEMERTIDAE.

Key to Genera Known to Occur in the Atlantic Oceans.

1. Mouth and proboscis united into a short atrium 2
1. Mouth and proboscis opening separate 3
2. Body broad and flat without distinct caudal fin ..... *Planktonemertes*
2. Body broad in middle third, narrowed at both ends, with caudal fin *Mononemertes*
3. Body short, broad and thick; caudal fin narrow and sharply demarcated from body; intestinal diverticula much divided, with well-developed ventral branches ..... *Crassonemertes*
3. Caudal fin slightly differentiated; intestinal diverticula without ventral branches ..... *Pachynemertes*

Genus ***Planktonemertes*** Woodworth.

7. ***Planktonemertes vanhoeffeni*** Brinkmann.

P. vanhoeffeni Brinkmann, 1915, 1917, 1917a; Coe, 1926.

Text-figure 8.

Known only from a single female collected by the German South Polar expedition in a net drawn from a depth of 3,000 meters to the surface in the South Atlantic Ocean west of the Cape of Good Hope.

Genus ***Mononemertes*** Coe.

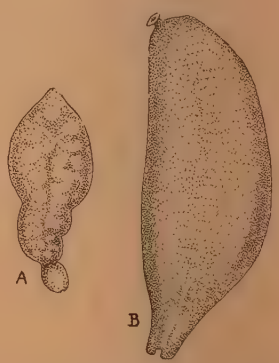
8. ***Mononemertes sargassicola*** (Joubin).

Planktonemertes sargassicola Joubin, 1906; *Mononemertes sargassicola* Coe, 1926.

Text-figure 9,A.

Known only from a single specimen collected in a net drawn from a depth of 2,225

TEXT-FIG. 8. *Planktonemertes vanhoeffeni* **A, B**, type specimen from dorsal and lateral surfaces respectively; **C**, stylet basis. (After Brinkmann).



TEXT-FIG. 9. **A**, *Mononemertes sargassicola* (after Joubin); **B**, *Crassonemertes robusta* (after Brinkmann).

meters to the surface by the Prince of Monaco expedition in the Sargasso Sea (Lat. 27°36′ N., Long. 38°29′ W.). The internal anatomy has not as yet been described.

9. ***Mononemertes scarlata*** new species.

Plate I, figures 1-8.

The type specimen of this new species was somewhat similar to that of *Planktonemertes vanhoeffeni* morphologically but differed in shape of body, in having a caudal fin, in having a dorsal core in each of the lateral nerve cords, in a less sharply curved stylet basis, in number of proboscidial nerves, and in other morphological details.

Body short and broad; oval in outline

ıd rather thin; narrowed posteriorly to ›rm a thin caudal fin which is not sharply ›marcated from body (Pl. I, fig. 1).

Length of type specimen, which repre-›nts a nearly sexually mature male, 15 m., width 9 mm., thickness 2 to 3 mm. ›lor in life scarlet.

Body walls. Musculature of body wall ›in, the longitudinal muscles being ar-ınged in separated bands. Although the ›dy is provided with a caudal fin, the re-ıction of the musculatures indicates an ability for rapid movements. Because of ›e low specific gravity due to the high ›ater content of the tissues, slight undula-›ry movements would be sufficient to keep ›e body suspended. Dorsoventral muscles ›e present in each of the interdiverticular ›aces but are highly developed only in the ıudal fin (Pl. I, fig. 1). The surface epi-›elium remained in place only on the ven-›al side in the posterior fourth of the body. ›here present, it is composed of slender ›liated and glandular cells and is some-›hat greater in thickness than that of the ıusculatures and basement layer combined ›l. I, fig. 4).

Proboscis sheath. Mouth and proboscis ›ening united into a short atrium when ›oboscis lies in natural position in body ›l. I, figs. 1, 2). Proboscis sheath about ›ven-eighths as long as body, terminating base of caudal fin. Musculature of pro-›scis sheath composed of interlacing long-ıdinal and circular or spiral fibers but ›th some indication of a three-layered ndition, since many of the circular fibers ›rm incomplete outer and inner layers ›th most of the longitudinal fibers be-›een them (Pl. I, fig. 5).

Proboscis large but less than twice as ıg as the body, loosely coiled in rhyn-ocoel. Posterior chamber short, with a ›ort retractor attached by means of in-›rlacing muscular fibers to the dorsal wall sheath near posterior end of latter. There ›re in the type specimen 17 distinct pro-›scidial nerves, with several additional en-›gements of the intermuscular nervous ›xus in the anterior portion of the organ, ›ere the number may appear to be 20 or . The armature consists of the usual form curved basis, asymmetrically crescentic optical section, with perhaps 20 or more ıall pits from which, in this specimen, the nute stylets had been dissolved (Pl. I, . 7). Accessory stylet pouches were not ınd.

Digestive system. The mouth opens from › atrium directly into the stomach, the ›phagus being absent as in some other thypelagic species. The walls of the ›mach are folded in such a manner as to ›dicate that they may be everted from the atrium to serve as lips to hold the prey at the time of feeding (Pl. I, fig. 2). The pylorus is short, with a correspondingly short caecum but the number of pairs of caecal diverticula could not be determined. There were in the type specimen about 40 pairs of intestinal diverticula, each with a broadly lobed but not profusely divided dorsal branch and a similar, but somewhat smaller ventral branch between the nerve cord and the body wall (Pl. I, fig. 3). The ventral branches become smaller posteriorly and disappear anterior to the caudal fin, allowing the nerve cord to come in contact with the ventral body wall (Pl. I, fig. 4).

Blood-vascular system. Lateral and dorsal vessels as in related genera. Dorsal vessel enters anterior end of rhynchocoel and remains on the ventral wall of this cavity throughout the length of the pylorus region; it then leaves the rhynchocoel and continues posteriorly on the ventral side of the proboscis sheath to the posterior end of that organ. Posterior to the proboscis sheath the dorsal vessel lies beneath the dorsal body wall and joins the lateral vessels in the caudal fin.

Nervous system. Lateral nerve cords with large ventral fibrous core and a much smaller and rather inconspicuous dorsal core (Pl. I, fig. 8).

Reproductive organs. The type specimen was a nearly mature male with 8 pairs of spermaries near the anterior end of the body (Pl. I, fig. 1). They are situated near the ventral sides of the nerve cords, the most anterior ones being close behind the brain. From each spermary a small spermatic duct leads to the ventral surface of the body.

Geographical distribution. This new species is as yet known only from a single individual collected in the Bermuda area at a depth of about 1,500 meters.

Type Specimen: Holotype, Cat. No. 31247; Net 1025; June 16, 1931. In the collections of the Department of Tropical Research, New York Zoological Park, New York City.

Genus **Crassonemertes** Brinkmann.

10. **Crassonemertes** (?) **rhomboidalis** (Joubin).

Planktonemertes rhomboidalis Joubin, 1906; *C.* (?) *rhomboidalis* Coe, 1926.

This species was described from the external appearance of the body only, and nothing is as yet known as to the internal morphology. Consequently the status of the species must remain doubtful until a more complete study of the type specimen is made. The specimen was collected in the Sargasso Sea in a net drawn from 2,000 meters to the surface.

11. ***Crassonemertes robusta*** Brinkmann.

Text-figure 9,B.

Brinkmann, 1917, 1917a; Coe, 1926, 1936; Wheeler, 1934.

This species is known from 3 specimens; 2 of these were females, while the sexuality of the other could not be determined. Hence the male remains undescribed. The type specimen was collected in the North Atlantic, northwest of Great Britain (Lat. 57°41′ N., Long. 11°48′ W.) at a depth of about 1,666 meters; the second came from the Bermuda area at a depth of 1,100 meters and the third from off the west coast of Africa (Lat. 6°55′ N., Long. 15°54′ W.). This distribution appears to cover a triangular area across the width of the North Atlantic and extends through more than 50 degrees of latitude. It is not known, however, whether the species occurs at intermediate localities but the ocean currents are such as to make a wide distribution probable (Text-fig. 1).

Genus ***Pachynemertes*** Coe.

12. ***Pachynemertes obesa*** Coe, 1936.

Text-figure 10.

Known only from the type specimen measuring 16 mm. in length, 8 mm. in width and 5 mm. in thickness. This was a mature female collected in the Bermuda area at a depth of about 1,600 meters.

TEXT-FIG. 10. *Pachynemertes obesa.* Strongly contracted specimen, showing mouth and everted proboscis; also stylet basis and several stylets. (After Coe).

FAMILY BUERGERIELLIDAE.

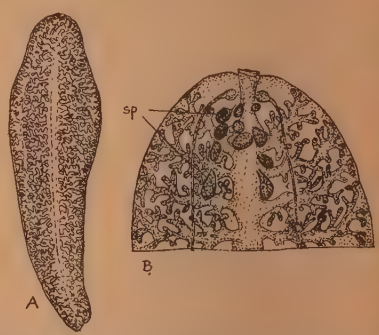
Genus ***Buergeriella*** Brinkmann.

13. ***Buergeriella notabilis*** Brinkmann, 1917.

B. notabilis Brinkmann, 1917a; Coe, 1926.

Text-figure 11.

Only a single representative of this species is at present known. This was a male 52 mm. in length, 15 mm. in greatest width and only 2.5 to 4 mm. in thickness. This was collected in the North Atlantic (Lat 48° 29′ N., Long. 13° 55′ W.) at a depth of 1,333 meters.



TEXT-FIG. 11. *Buergeriella notabilis.* **A**, type specimen, showing profusely branched intestinal diverticula; **B**, anterior end of body, showing spermaries **(sp)**. (After Brinkmann).

FAMILY DINONEMERTIDAE.

Key to Genera at Present Known from the Atlantic Oceans.

1. Mouth on ventral surface of head, well separated from rhynchodeal opening; proboscis sheath almost as long as body; wall of sheath of interwoven longitudinal and circular fibers ..... *Paradinonemertes*

1. Mouth anterior to brain; wall of proboscis sheath composed of separate muscular layers 2

2. Proboscis sheath limited to anterior two-thirds of body..... *Dinonemertes*

2. Proboscis sheath nearly as long as body ..... *Planonemertes*

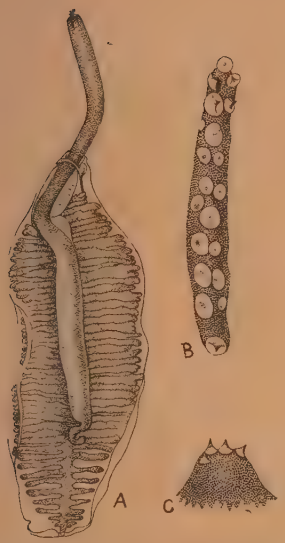
Genus ***Paradinonemertes*** Brinkmann.

14. ***Paradinonemertes drygalskii*** Brinkmann.

P. drygalskii Brinkmann, 1915, 1917; Coe, 1926.

Text-figure 12.

Two representatives of this species, both of which were males, were taken by the *Michael Sars* expedition in the North Atlantic west of the Cape Verde Islands (Lat. 17°28′ N., Long. 29°42′ W.) in a net drawn from a depth of 3,000 meters to the surface.



TEXT-FIG. 12. *Paradinonemertes drygalskii.* **A,** outline of body, showing unbranched intestinal diverticula and extent of proboscis sheath; **B,** stylet basis; **C,** transverse section of basis with stylets. (After Brinkmann).

15. ***Paradinonemertes wheeleri*** Coe, 1936.
Text-figure 13.

Six individuals belonging to this species were obtained in the Bermuda area. The body is broad, flat and thin, with broad caudal fin not sharply demarcated from body. The length of these specimens varied from 11 to 42 mm. and the width from 4 to 15 mm. The males have 3 to 5 spermaries in an irregular row on each side of the body close behind the brain and mature females 30 to 36 pairs of ovaries.

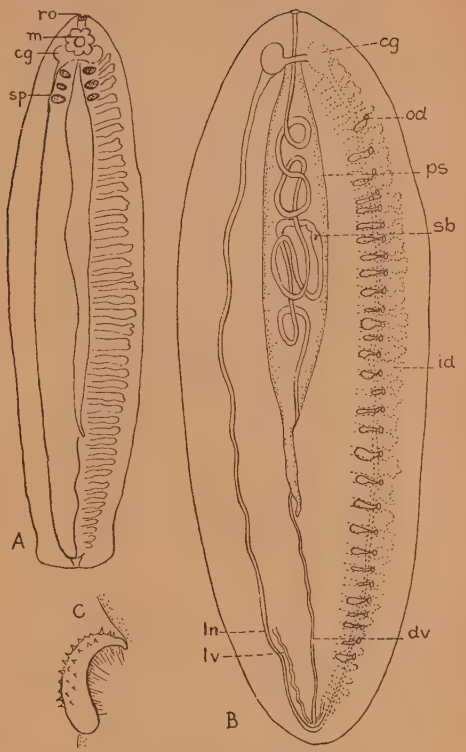
This species is known only from the Bermuda area, where it was found to live at depths of 1,400 to 1,800 meters.

Genus ***Dinonemertes*** Laidlaw.

16. ***Dinonemertes alberti*** (Joubin).
Planktonemertes alberti Joubin, 1906; *D. alberti* Brinkmann, 1917; Coe, 1926.
Text-figure 14,A.

In this, as in other species of the genus, the body is broad, flat and thin, with nearly parallel lateral margins. The type specimen was 85 mm. long and 27 mm. wide, while the three other individuals which have thus far been collected were from 66.5 to 76 mm. in length and from 19 to 22 mm. in width.

The male, as figured by Joubin, has a row of 6 or more closely placed spermaries on each side of the body back of the brain. The females have 18 to 25 pairs of ovaries.

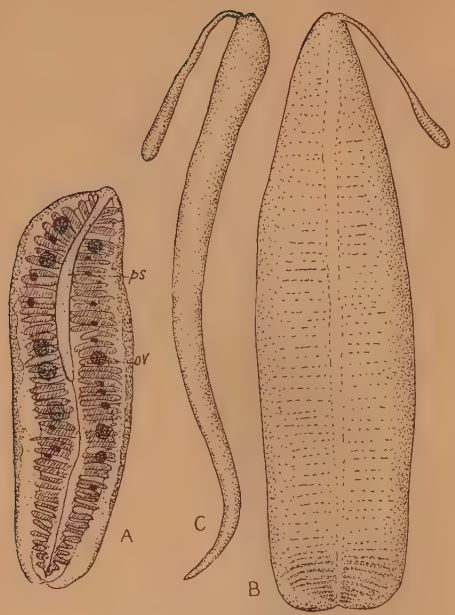


TEXT-FIG. 13. *Paradinonemertes wheeleri.* **A,** male with 3 pairs of spermaries **(sp)**; **B,** female with 30 pairs of ovaries and oviducts **(od)**; other letters indicate: **cg,** cerebral ganglia; **dv,** dorsal vessel; **id,** intestinal diverticula; **ln,** lateral nerve cord; **lv,** lateral vessel; **m,** mouth; **ps,** proboscis sheath; **ro,** rhynchodeal opening; **sb,** stylet basis of proboscis; **C,** stylet basis with minute stylets. (After Coe).

This species has been found only in the northern part of the North Atlantic (Lat. 63° to 71° N.), between Greenland and Norway. The nets were lowered to depths of 1,300 to 3,300 meters and drawn to the surface.

17. ***Dinonemertes grimaldii*** (Joubin).
Planktonemertes grimaldii Joubin, 1906; *D. grimaldii* Brinkmann, 1917; Coe, 1926.

The two specimens, each about 40 mm. long and 10 mm. wide, which Joubin considered as representing a species distinct from *D. alberti,* have as yet been studied only superfically. Until the essential features of the internal anatomy are known the status of the species must remain in doubt. The specimens were collected in the middle North Atlantic (Lat. 31° to 37° N.) between 3,000 meters and the surface.



Joubin; **B**, **C**, after Brinkmann).
showing intestinal diverticula, ovaries **(ov)** and short proboscis sheath **(ps)**. **B**, **C**, dorsal and lateral views of *D. investigatoris*. (**A** after Joubin; **B**, **C**, after Brinkmann).

18. ***Dinonemertes investigatoris*** Laidlaw, 1906.
D. investigatoris Brinkmann, 1917, 1917a; Coe, 1926.

Text-figure 14,B,C.

Individuals of this species are the giants among the bathypelagic nemerteans, the broad and flat body of the three specimens thus far obtained measuring from 107 to 203 mm. in length and 23 to 56 mm. in width. All were mature females.

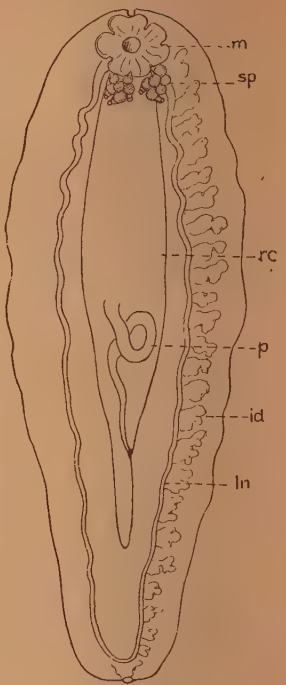
The type specimen was taken from a depth of about 2,000 meters in the Indian Ocean, southwest of India. Two other specimens which Brinkmann (1917) referred to this species were collected in the middle North Atlantic (Lat. 34° and 48°) in nets lowered to 2,000 meters. If Brinkmann was correct in his identification, this species has a wider geographical range than is known for any other bathypelagic nemertean, with the exception of *Pelagonemertes rollestoni*. No examples have as yet been found at intermediate stations. Only these two species have been collected both in the Indian Ocean and in the North Atlantic.

Genus ***Planonemertes*** Coe.

19. ***Planonemertes labiata*** Coe, 1936.

Text-figure 15.

This species is known only from the Ber-



TEXT-FIG. 15. *Planonemertes labiata*. Outline of body of male, showing spermaries **(sp)**, extent of rhynchocoel **(rc)** with posterior attachment of proboscis **(p)**, lobed intestinal diverticula **(id)**, mouth with everted lips **(m)** and lateral nerve cord **(ln)**. (After Coe).

muda area, where two individuals, one male and one female, were taken at a depth of about 1,800 meters.

FAMILY PHALLONEMERTIDAE.

Genus ***Phallonemertes*** Brinkmann.

20. ***Phallonemertes murrayi*** (Brinkmann).

Bathynectes murrayi Brinkmann, 1912, 1917, 1917a; *P. murrayi* Brinkmann, 1917; Coe, 1926, 1936.

Text-figure 16.

Two specimens of this species were taken in the Bermuda area at depths of 1,500 and 1,800 meters. Previously reported from various localities in the North Atlantic from Lat. 35° N. to near the southern point of Greenland at depths of 1,600 to 2,000 meters.

FAMILY CHUNIELLIDAE.

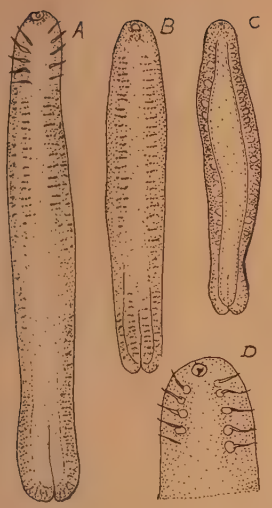
Genus ***Chuniella*** Brinkmann.

21. ***Chuniella agassizii*** (Bürger).

Planktonemertes agassizii Bürger, 1909; *C. agassizii* Brinkmann, 1917; Coe, 1926.

Text-figure 17, B, C.

The single known representative of this



TEXT-FIG. 16. *Phallonemertes murrayi.* **A, D,** males with external, tubular genital papillae; **B, C,** females. (After Brinkmann).

species was an immature female collected in the equatorial Atlantic (Lat. 9°N.) off the coast of Sierra Leone, Africa, in a net drawn from a depth of 1,300 meters.

22. ***Chuniella*** (?) ***elongata*** (Joubin).

Planktonemertes elongata Joubin, 1906; *C.* (?) *elongata* Brinkmann, 1917; Coe, 1926.

As only the type specimen is known and this has been described only superficially, the status of this species still remains in doubt. The specimen was taken near the middle of the North Atlantic (Lat. 34° N.) in a net drawn from 4,000 meters to the surface.

23. ***Chuniella lanceolata*** Brinkmann, 1917.

C. lanceolata Coe, 1926.

Text-figure 17, A.

Only two specimens of this species have been discovered up to the present time. One of these was a female taken at a depth of about 1,600 meters in the Bermuda area, while the type specimen was a male collected in the North Atlantic (Lat. 48° 29′ N.) southwest of Ireland in a net lowered to only 1,000 meters.

FAMILY NECTONEMERTIDAE.

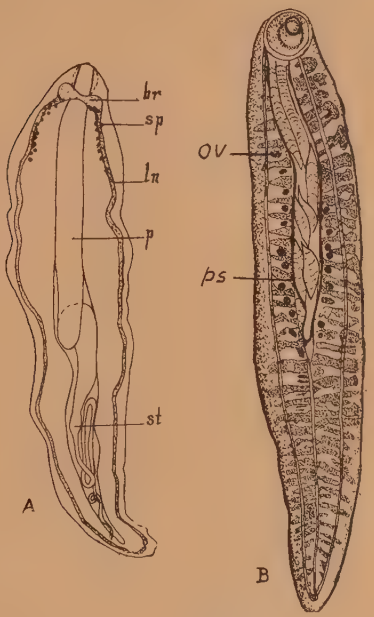
Genus ***Nectonemertes*** Verrill.

4. ***Nectonemertes minima*** Brinkmann, 1915.

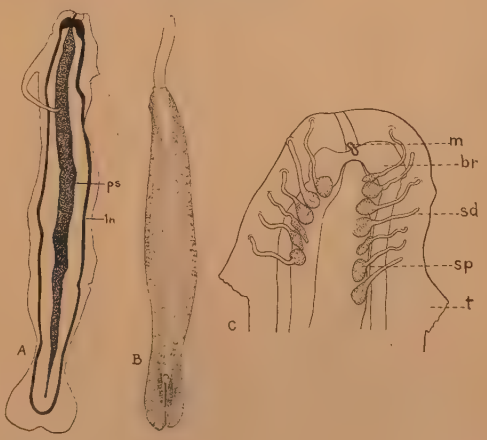
Hyalonemertes atlantica Bürger, 1909; *N. minima* Brinkmann, 1917, 1917a; Coe, 1926.

Text-figure 18.

This species is widely distributed in the eastern North and South Atlantic oceans from 57° north latitude to 35° south latitude. This range of 92 degrees of latitude extends from a point northwest of Ireland,



TEXT-FIG. 17. **A,** *Chuniella lanceolata,* male showing spermaries **(sp)** in an irregular row behind the brain **(br),** the long proboscis **(p)** with stylet chamber **(st)** and the lateral nerve cords **(ln). B,** *C. agassizii,* female with ovaries **(ov)** and short proboscis sheath **(ps).** (**A** after Brinkmann, **B** after Bürger).



TEXT-FIG. 18. *Nectonemertes minima.* **A,** outline of body of male; **B,** female; **C,** anterior end of body of male, showing position of spermaries **(sp);** other letters indicate: **br,** brain; **ln,** lateral nerve cord; **m,** mouth; **ps,** proboscis sheath; **sd,** sperm duct; **t,** base of tentacle. (After Brinkmann).

across the equator to near the Cape of Good Hope.

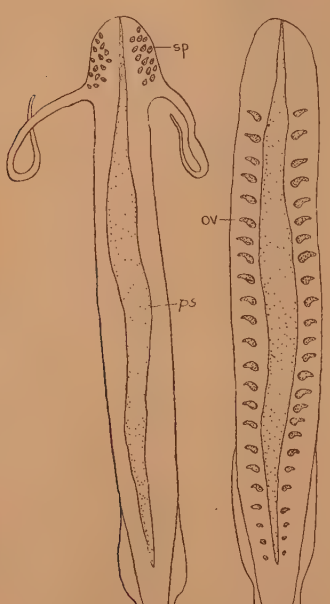
The males are distinguished from those of *N. mirabilis* and *N. primitiva* in having 5 to 7 spermaries on each side of the body back of the head. The female has about 25 pairs of ovaries.

25. **Nectonemertes mirabilis** Verrill.

N. mirabilis (*Hyalonemertes atlantica*) Verrill, 1892; Brinkmann, 1917, 1917a; Coe and Ball, 1920; Coe, 1926, 1936; Wheeler, 1934; *N. grimaldii* Joubin, 1904, 1906; *N. kempi* (?) Wheeler, 1934.

Text-figure 19.

The collections previously reported from the Bermuda area (Coe, 1935, 1936) contained 32 representatives of this species. The supplementary collections from the same area included 12 additional specimens. These represented both sexes and various stages of sexual maturity. One of these was caught at a depth of about 1,100 meters, 6 at 1,300 m., 2 at 1,460 m., 1 at 1,640 m. and 2 at 1,830 m.



TEXT-FIG. 19. *Nectonemertes mirabilis.* **A**, male with cephalic spermaries **(sp)**; **B**, female with 23 pairs of ovaries **(ov)**; **ps**, proboscis sheath.

The 32 specimens of this species previously obtained from this area came from depths of 900 to 1,830 meters, with the largest numbers coming from near the maximum depth. Consequently it may be surmised that the species might also have been found if the nets had been lowered to somewhat deeper levels. The range is from 500 to 2,000 meters but the greater portion of population seems to be limited to a rather definite water layer having a temperature of 3.5° to 5° C. and a salinity of about 3.5 per cent. This layer is found at a depth of 1,200 to 2,000 meters in the Bermuda area but is nearer the surface in the northern part of the North Atlantic. There the species is found at a correspondingly higher level.

This species has a wide range of geographical distribution, being found throughout the North Atlantic Ocean from near Cuba to the latitude of southern Greenland and from the American to the European continental slopes. It also extends southward through the tropics to the South Atlantic in the latitude of South Africa (Text-fig. 1). It appears to be by far the most abundant of all the bathypelagic nemerteans which up to the present time have been discovered in the North Atlantic Ocean.

The morphological characteristics of this species have been described in detail by Coe and Ball (1920). The colors of the females in life are described as yellow or orange and of the males red or scarlet. The young are paler, sometimes white.

Wheeler (1934) reported from the eastern equatorial Atlantic (Lat. 7° N., Long. 16° W.) a specimen which he supposed to represent a new species which he described as *N. kempi.* There is nothing in his description, however, which does not apply equally well to young individuals of *N. mirabilis.* Therefore there seems to be no good reason for considering *N. kempi* to be a valid species.

26. **Nectonemertes primitiva** Brinkmann, 1917, 1917a.

N. primitiva Coe, 1926; *Nectonemertes mirabilis* Bürger, 1909.

Text-figure 20.

One of the three known representatives of this species was taken in the equatorial Atlantic (Lat. 3°55′ S., Long. 7°48′ W.) off the west coast of French Congo in a vertical haul from 3,000 meters; the other two come from the central North Atlantic (Lat. 31° N., Long. 35° W. and Lat. 35° N., 33° W.) at depths of 666 and 2,000 meters respectively.

The male is distinguished from that of *N. mirabilis* in having a single row of 4 to 6 spermaries on each side of the body close behind the brain (Text-fig. 20), while the female has about 10 pairs of ovaries.

TEXT-FIG. 20. *Nectonemertes primitiva*. **A**, outline of body of living individual, with slender body and tentacles (after Bürger). **B**, lateral and ventral views of male with body contracted after preservation; **sp**, spermaries; **C**, female (after Brinkmann).

FAMILY ARMAUERIIDAE.

Genus ***Armaueria*** Brinkmann.

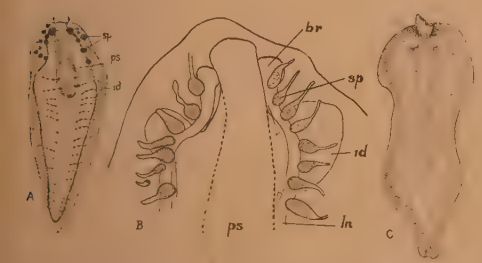
27. ***Armaueria rubra*** Brinkmann, 1917.

A. rubra Coe, 1926.

Text-figure 21.

Individuals of this species are small, even when sexually mature, the four known representatives being only 5.3 to 9.5 mm. in length and 2 to 7 mm. in width. The proboscis sheath is limited to the anterior half of the body (Text-fig. 21). The male has 8 to 12 spermaries in an irregular row on each side of the body close behind the brain (Text-fig. 21), while the single female at present known has 8 pairs of ovaries.

Known only from the central North Atlantic (Lat. 45° to 55° N., Long. 25° to 43° W.), where four specimens were collected at depths of 800 to 1,600 meters.



TEXT-FIG. 21. *Armaueria rubra*. **A**, male, showing spermaries **(sp)** and short proboscis sheath **(ps)**; **B**, anterior end of body of male, showing position of spermaries **(sp)** relative to brain **(br)**; **C**, female, showing dorsal position of rhynchodeal opening; other letters indicate: **id**, caecal diverticulum; **ln**, lateral nerve cord. (After Brinkmann).

FAMILY PELAGONEMERTIDAE.

Key to Genera Found in the Atlantic Oceans.

1. Body pointed at posterior end, without caudal fin 2
1. Body with more or less well demarcated caudal fin 3
2. Spermaries in a single row on each side of body near brain *Gelanemertes*
2. Spermaries in a compact group on each side of body near brain *Natonemertes*
3. Caudal fin not distinctly demarcated..... *Parabalaenanemertes*
3. Caudal fin well developed 4
4. Intestinal diverticula closely appressed *Probalaenanemertes*
4. Intestinal diverticula separated by much gelatinous tissue..... *Pelagonemertes*

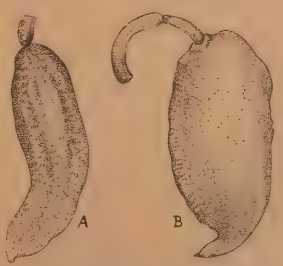
Genus ***Natonemertes*** Brinkmann.

28. ***Natonemertes acutocaudata*** Brinkmann, 1917.

N. acutocaudata Coe, 1926.

Text-figure 22.

Only two representatives of this species are at present known. Both were males with a compact group of four or five spermaries on each side immediately posterior to the brain. They were collected in the northern part of the North Atlantic (Lat. 58° to 61° N., Long. 12° to 17° W.) in a net lowered to depths of 1,200 to 1,400 meters.



TEXT-FIG. 22. *Natonemertes acutocaudata* in different states of contraction. (After Brinkmann).

Genus ***Gelanemertes*** Coe.

29. ***Gelanemertes richardi*** (Joubin).

Pelagonemertes richardi Joubin, 1906; *G. richardi* Coe, 1926.

The single known representative of this species has not yet been studied sufficiently

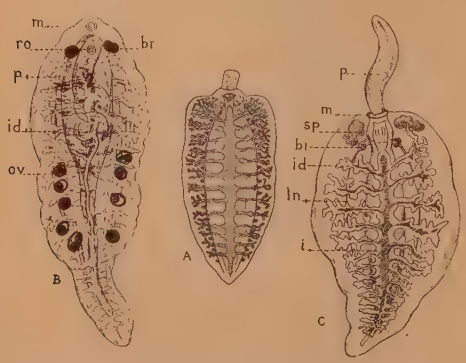
to determine the details of the internal anatomy. The general appearance of the body resembles that of species of *Pelagonemertes* but indicates a different genus because the spermaries are situated in a single row on each side of the body. This specimen was taken in the central North Atlantic (Lat. 30°36′ N., Long. 26°05′ W.).

Genus ***Pelagonemertes*** Moseley, 1875.

30. ***Pelagonemertes rollestoni*** Bürger, 1909; Brinkmann, 1915, 1917; Coe, 1926; Wheeler, 1934.

Text-fig. 23.

This appears to be one of the most abundant as well as the most widely distributed of all the bathypelagic species. It has been taken in the equatorial Atlantic (Lat. 0° N., Long. 7° W.) off the west coast of Africa, across almost the entire width of the South Atlantic at 30° to 50° of latitude, near Ceylon in the Indian Ocean (Lat. 5° N.) and in the ocean far south of Australia (Lat. 50° S., 123° W.) This indicates a range of 55 degrees of latitude and 130 degrees of longitude. Some of the specimens were taken in closing nets at depths of 700 to 950 meters, while the others were caught in open nets lowered to depths of 1,000 to 3,500 meters.



TEXT-FIG. 23. *Pelagonemertes rollestoni*. **A**, female with 13 pairs of small ovaries (after Moseley). **B**, female; **C**, male (after Bürger). Letters indicate: **br**, brain; **i**, intestine; **id**, intestinal diverticula; **ln**, lateral nerve cord; **m**, mouth; **ov**, ovaries; **p**, proboscis; **ro**, rhynchodeal opening; **sp**, spermaries.

Genus ***Parabalaenanemertes*** Brinkmann.

31. ***Parabalaenanemertes fusca*** Brinkmann, 1917.

P. fusca Coe, 1926.

The three known specimens, one male and two females, were taken in the northern part of the central North Atlantic (Lat. 46° to 55° N., Long. 7° to 28° W.) at depths of 650 to 1,800 meters.

32. ***Parabalaenanemertes nigra***, new species.

Plate II, figs. 1-5.

One female which evidently represents a new species of this genus was found among the collections made in 1931. This specimen resembled in many respects the corresponding sex of *P. fusca* as described by Brinkmann (1917) but when sectioned was found to differ in having but a single fibrous core in each of the lateral nerve cords, in having an almost complete lack of dorsoventral muscular fibers even in the posterior end of the body, in having both dorsal and ventral branches of the intestinal diverticula profusely branched, in a much larger and longer proboscis, in having the long posterior chamber of the proboscis deeply pigmented and in other details.

This specimen was small, although it was sexually mature. The body was oval in shape, narrowed at both ends but more slender posteriorly and only slightly flattened (Pl. II, fig. 1). It measured 7 mm. in length, 3 mm. in greatest width and 2 mm. in thickness. It should be mentioned that one of the females of *P. fusca* studied by Brinkmann was of exactly the same dimensions.

Color. The specimen was labeled by the collector "black worm," presumably as an indication of the color in life. After preservation for ten years, however, the color had mostly disappeared except for the intensely black pigmentation of the long posterior chamber of the proboscis. There remained also some traces of the original pigment in the granular contents of the intestinal diverticula.

Body walls. The musculature of the body walls is remarkably thin, especially toward the lateral margins of the body. The basement layer which in life supports the surface epithelium is likewise much thinner than in most bathypelagic nemerteans but it has the usual cup-like depressions to allow for the firm attachment of the epithelial cells. As so often happens with these worms, most of the epithelium was lost at the time of collection.

Proboscis sheath. The rhynchodeum opens at the tip of the head, immediately dorsal to the mouth. The proboscis sheath extends the entire length of the body and is so large that it occupies about three-fourths the vertical axis of the body in the median line and about one-third the width of the body. Its musculature is generally three to six times as thick as that of the body wall and is arranged in two distinct layers. Of these the outer is spiral and the inner longitudinal. The spiral layer is about twice as thick as the longitudinal layer and both are

considerably thinner along the ventral side than elsewhere (Pl. II, fig. 3).

At the anterior end of the sheath, in the brain region, the muscular layers are more or less distinctly reversed, the separated bundles of longitudinal muscles being bordered internally by a layer of circular muscles and externally by a thin layer of spiral fibers. For a short distance posterior to the brain region the spiral and longitudinal bundles are interlaced but in the region of the foregut the longitudinal fibers become separated into a distinct internal layer. That relation of the two layers continues throughout the rest of the body.

Through the anterior four-fifths of the body the sheath remains nearly uniform in diameter, the rhynchocoel being nearly filled with the three loops of the proboscis. The sheath then becomes somewhat enlarged to accommodate the many loops of the posterior chamber of the proboscis (Pl. II, fig. 1). The terminal portion of the sheath is narrowly constricted but the musculatures remain thick enough to allow a firm attachment for the interlacing fibers of the proboscis retractor muscles.

Proboscis. This organ is much larger than in most bathypelagic species and with its long retractor measures between four and five times the length of the body. In this type specimen, although the proboscis was partially everted at the time of preservation, it remains in three longitudinal loops, each of which is nearly as long as the body (Pl. II, fig. 1). The narrowed posterior end of the sheath retains its thick, two-layered walls and the long retractor is interlaced with the musculature of the dorsal wall (Pl. II, fig. 1).

The middle chamber is provided with a curved, spoon-shaped basis which in life must have borne a dozen or more stylets, but the latter had been dissolved in the preserved specimen. Accessory stylets were also missing. There are 12 large proboscidial nerves which occupy the usual positions in the distal portion of the longitudinal muscular layer. The external and internal circular musculatures are relatively thin.

The posterior chamber of the proboscis is itself longer than the body, being looped back on itself repeatedly in the widened posterior portion of the sheath (Pl. II, fig. 1). In a single transverse section of the body there were as many as nine sections of these loops. The epithelial cells of this portion of the proboscis form an intensely black secretion which retains its pigmentation for at least ten years after preservation. This black pigment appears in conspicuous patches in the preserved specimen and doubtless presented a characteristic feature of the body in life.

Digestive system. The mouth and rhynchodeum open separately. The epithelium lining the mouth is much folded, the outer folds protruding beyond the ventral surface of the head as a circle of folded lips (Pl. II, fig. 1). The size of the mouth indicates that the worm is capable of ingesting comparatively large objects but as the digestive organs were empty, no information as to the nature of the prey is available. Other bathypelagic nemerteans are known to feed upon various worms and crustaceans.

The foregut, including pylorus, is very short, necessitating an equally short caecum. The single pair of caecal diverticula, which extend forward to the dorsal side of the brain, are profusely branched. The diverticula of the midgut are correspondingly branched, with a profusion of lobules extending laterally on both dorsal and ventral sides of the nerve cords (Pl. II, figs. 4, 5). This type specimen had 12 pairs of well-formed diverticula, in addition to three small posterior pairs with small lobes only (Pl. II, fig. 1).

Blood-vascular system. Cephalic lacunae and lateral vessels are present in the usual positions. A rudimentary dorsal vessel lies beneath the proboscis sheath for a short distance posterior to the brain region and then enters the rhynchocoel. It terminates in a small lacuna a fraction of a millimeter farther back.

Nervous system. The brain is so large that it fills most of the space within the cephalic walls in the region that it occupies. The lateral nerve cords extend posteriorly between the dorsal and ventral branches of the midgut diverticula and about equidistant between the proboscis sheath and the lateral margins of the body. There is only a single fibrous core (Pl. II, fig. 2). No trace of the dorsal core which Brinkmann (1907) describes and figures for *P. fusca* could be recognized. A thin sheet of nerve-cord muscles extends along the dorsomedian surface.

The dorsal nerve is small and inconspicuous, as is usually the case with species having very thin body musculatures.

Reproductive system. The only specimen available for study was a mature female with 10 pairs of ovaries, each with a closed oviduct leading to the ventral surface of the body. The ovaries occupy the usual positions between adjacent intestinal diverticula and with one exception on the dorsal sides of the nerve cords (Pl. II, figs. 1, 5). The ovary produces but one or two mature ova at any one time and this specimen offers no evidence as to whether the oviduct opens to allow the egg to be fertilized before it is discharged from the body. The mature ovum is large and is provided with thousands of deeply-stained yolk granules.

In addition to the one or two large ova, the ovary contains several small ovocytes without yolk and these presumably begin in sequence to form yolk as soon as the mature ovum has been discharged. It is uncertain whether development of the embryo may begin within the body, for no evidence to that effect has yet been found in any of the bathypelagic species.

Habitat. The single known representative of this species was taken in the Bermuda area at a depth of about 1,200 meters.

Type Specimen: Holotype, Cat. No. 311-599; Net 1217; August 24, 1931. Deposited in the collections of the Department of Tropical Research, New York Zoological Park, New York City.

33. ***Parabalaenanemertes*** (?) ***zonata*** (Joubin).

Planktonemertes zonata Joubin, 1906; *Parabalaenanemertes* (?) *zonata* Coe, 1926.

Two specimens, which have as yet been studied only superficially, were collected in the central North Atlantic in nets drawn from 3,000 meters to the surface.

Genus ***Probalaenanemertes*** Brinkmann.

34. ***Probalaenanemertes irenae*** Wheeler, 1934.

The two known representatives of this species were taken in the South Atlantic west of the Cape of Good Hope in a net drawn from a depth of 1,000 meters. Both were females. They were associated with *Protopelagonemertes hubrechti* and *Pelagonemertes rollestoni.*

35. ***Probalaenanemertes wijnhoffi*** Brinkmann, 1917.

P. wijnhoffi Coe, 1926.

The single known individual of this species, which was a mature female, was taken in the northern part of the North Atlantic (Lat. 56° N., Long. 31° W.) at a depth of about 800 meters.

Family BALAENANEMERTIDAE.

Genus ***Balaenanemertes*** Bürger.

36. ***Balaenanemertes chavesi*** (Joubin).

Nectonemertes chavesi Joubin, 1906; *Balaenanemertes chavesi* Brinkmann, 1917; Coe, 1926.

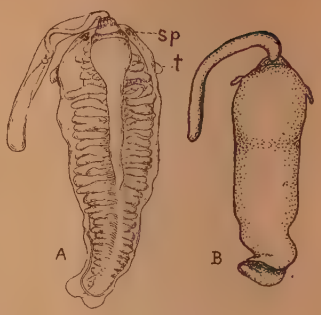
Text-figure 24, A.

The single known specimen was taken in the central North Atlantic in a vertical haul from 3,000 meters.

37. ***Balaenanemertes grandis*** Brinkmann, 1917.

B. grandis Coe, 1926.

The two known representatives of this species were taken in the northern North Atlantic at depths of 660 and 1,200 meters, respectively.



Text-fig. 24. **A**, *Balaenanemertes chavesi*, dorsal surface of male, showing spermaries **(sp)** and tentacles **(t)**; **B**, *B. lobata*, female, body contracted after preservation. (**A** after Joubin **B**, after Brinkmann).

38. ***Balaenanemertes hjorti*** Brinkmann, 1917.

B. hjorti Coe, 1926.

Only a single individual has as yet been obtained; it was collected in the central North Atlantic at a depth of about 1,000 meters.

39. ***Balaenanemertes lata*** Brinkmann, 1917.

B. lata Coe, 1926.

This species is likewise known from but a single specimen taken from a depth of about 1,300 meters in the central North Atlantic.

40. ***Balaenanemertes lobata*** (Joubin).

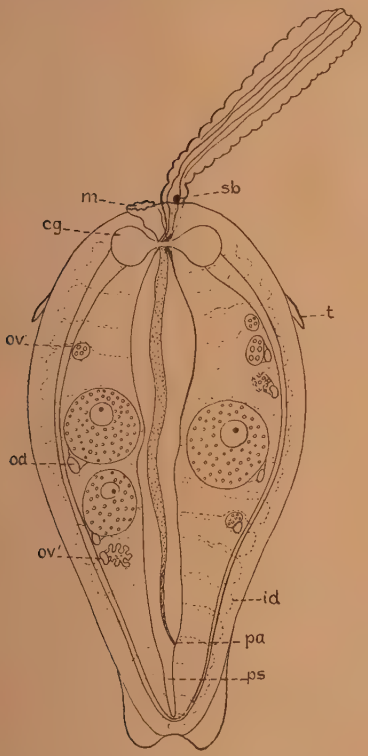
Nectonemertes lobata Joubin, 1906; *Balaenanemertes lobata* Brinkmann, 1917; Coe, 1926. (Includes *B. musculocaudata* Brinkmann?).

Text-figure 24, B.

Eight individuals which have been referred to this species have been taken in the central and northern North Atlantic (Lat. 36° to 59° N.) in nets lowered to depths of 400 to 3,000 meters. Seven of these were females; at three stations the females were associated with males of *B. musculocaudata,* which are closely similar anatomically except for the gonads but differ in color. Brinkmann himself suggests that such anatomical differences as he found might be merely sexual distinctions. If this supposition is correct, the name *B. musculocaudata* is a synonym of *B. lobata.* In several species of bathypelagic nemerteans the two sexes differ in color.

41. ***Balaenanemertes minor*** Coe, 1926.
Text-figure 25.

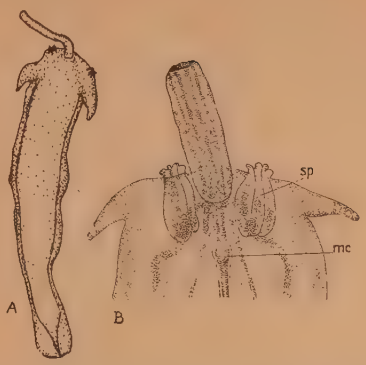
This species is known only from the Bermuda area, where a single individual was caught at a depth of 549 meters.



TEXT-FIG. 25. *Balaenanemertes minor*. Outline of body of mature female with partially everted proboscis, showing 3 large ovaries each containing a single ripe ovum and 6 small ovaries (**ov, ov'**) from which the eggs have been discharged; other letters indicate: **cg**, cerebral ganglia; **id**, intestinal diverticula; **m**, mouth; **od**, oviduct; **pa**, attachment of proboscis to proboscis sheath (**ps**); **sb**, stylet basis; **t**, tentacle. (After Coe).

42 (?). ***Balaenanemertes musculocaudata*** Brinkmann, 1917.
B. lobata (Joubin)?
B. musculocaudata Coe, 1926.
Text-figure 26.

The five individuals thus far obtained were all males; they were collected in the northern North Atlantic; at three stations they were associated with females of *B. lobata*. For the reasons stated above it seems probable that these males actually represent the latter species, but it seems advisable to retain both specific names until further evidence is available.



TEXT-FIG. 26. *Balaenanemertes musculocaudata* (*lobata?*). **A**, male with partially everted proboscis; **B**, anterior end of body, showing spermaries (**sp**) and middle chamber of proboscis (**mc**). (After Brinkmann).

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EXPLANATION OF THE PLATES.

PLATE I.

Mononemertes scarlata.

Fig. 1. Outline of body, showing extent of proboscis sheath and proboscis; on one side the 8 spermaries are indicated and on the other side the lobed intestinal diverticula.

Fig. 2. Diagram of anterior end of body, indicating relation of proboscis and mouth, which open together into a short atrium.

Fig. 3. Portion of transverse section of body, showing dorsal and ventral branches of one of the intestinal diverticula.

Fig. 4. Portion of transverse section near posterior end of body, showing intestinal diverticulum without ventral branch. The epithelium covering entire body wall in life is still retained on ventral surface.

Fig. 5. Portion of transverse section of proboscis sheath, showing interlacing of longitudinal and circular or spiral muscular fibers.

Fig. 6. Portion of section through caudal fin, with commissure at posterior end of nerve cords and the well developed dorsoventral musculature.

Fig. 7. Outline of stylet basis, with indications of sockets from which the minute stylets have been dissolved.

Fig. 8. Transverse and longitudinal sections of lateral nerve cord, showing dorsal fibrous core **(dc)**.

Letters indicate: **a**, atrium; **bm**, basement layer underlying surface epithelium in life; **br**, brain; **cf**, caudal fin; **db**, dorsal branch of intestinal diverticulum; **dc**, dorsal core of nerve fibers; **dv**, dorsal blood vessel; **dvm**, dorsoventral muscles; **ep**, epithelium; **ln**, lateral nerve cord; **lv**, lateral vessel; **m**, mouth; **nc**, nerve-cord commissure; **p**, proboscis; **ps**, proboscis sheath; **py**, pylorus; **r**, rectum; **rc**, rhynchocoel; **sp**, spermaries; **st**, stomach; **sty**, stylet basis; **vb**, ventral branch of intestinal diverticulum.

PLATE II.

Parabalaenanemertes nigra.

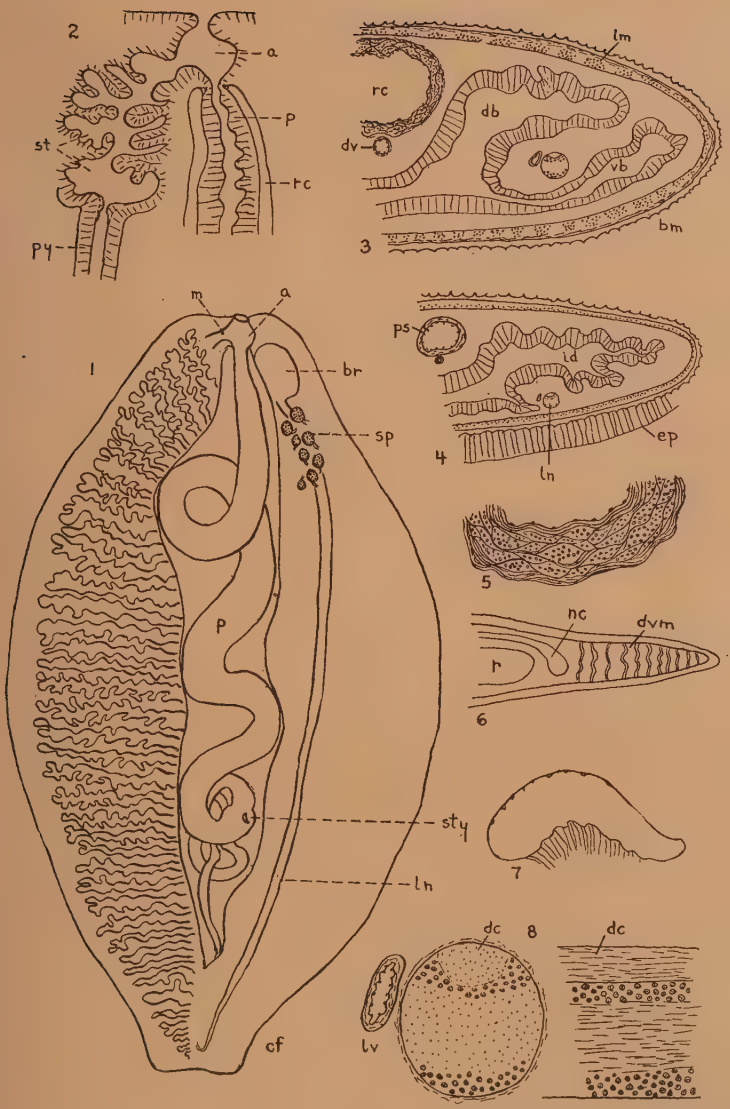
Fig. 1. Outline of body of type specimen, showing intestinal diverticula on one side of the body and ovaries **(ov)** on the other side, with the rhynchocoel containing the extremely long, coiled proboscis occupying the central axis; other letters indicate: **br**, brain; **ln**, lateral nerve cord; **m**, mouth; **pc**, posterior chamber of proboscis; **sb**, stylet basis; **rm**, retractor muscle.

Fig. 2. Transverse section of lateral nerve cord with accompanying nerve-cord muscle **(ncm)** and lateral vessel **(lv)**.

Fig. 3. Portion of transverse section of proboscis sheath with dorsal vessel **(dv)**; **cm** and **lm**, circular and longitudinal muscular layers respectively.

Fig. 4. Portion of transverse section of body, showing the dorsal **(dbr)** and ventral **(vbr)** branches of the intestinal diverticula; **rc**, rhynchocoel; **ln**, lateral nerve cord with accompanying vessel and nerve cord muscle.

Fig. 5. Portion of transverse section in posterior third of body showing the ovary and oviduct **(od)**; letters as in Fig. 4.



BATHYPELAGIC NEMERTEANS OF THE BERMUDA AREA AND OTHER PARTS OF THE NORTH AND SOUTH ATLANTIC OCEANS, WITH EVIDENCE AS TO THEIR MEANS OF DISPERSAL.

BATHYPELAGIC NEMERTEANS OF THE BERMUDA AREA AND OTHER PARTS OF THE NORTH AND SOUTH ATLANTIC OCEANS, WITH EVIDENCE AS TO THEIR MEANS OF DISPERSAL.

Contribution No. 262

Reprinted from Copeia, 1945, No. 3, October 15

The Record of a Fish, *Scorpaena mystes*, from California: A Comedy of Errors [1]

By Carl L. Hubbs

IN preparing a much needed check-list of the fishes of California W. I. Follett becomes concerned with what he rightly regards as "the seemingly improbable record" of *Scorpaena mystes* from this state. He suggests that I check on the material in the Scripps Institution of Oceanography on which Fowler (1923: 299) based his La Jolla record of *Scorpaena mistes* [sic] Jordan and Starks. Following through with this suggestion I find in the Scripps Institution collection one specimen, labelled *Scorpaena mystes*, which must have been the basis for the single California record of this tropical American Pacific species. There are no other examples of this species in the collection and no mention of any others on the card index.

From an examination of this specimen and of the corresponding card it seems certain that *Scorpaena mystes* has been reported by error from California. In the first place the fish in question (S.I.O., No. 99) is totally without data, other than the statement that it was collected by the "Inst."

[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 262.

This makes it probable but by no means certain that the example was collected locally. Hence even if the identification were correct, which it is not, the record for California would hardly have been justified. The specimen proves, as was expected, to be a misidentified example of the locally abundant California "sculpin," *Scorpaena guttata* Girard, the only species of the genus definitely known from California. The one record of another species from the state—that of Evermann and Latimer (1910: 137) for *Scorpaena histrio* from San Pedro—will presumably also prove to have been based on *S. guttata.*

In the specimen erroneously identified as *Scorpaena mystes* the dorsal rays number XII, 8, not XII, 10 as is generally reported for both *guttata* and *mystes*. Since other examples of *guttata* examined have 9 dorsal soft-rays the reduction to 8 may be assumed to be an individual variation. Apparently Jordan and Evermann (1898: 1839–1854) and some other authors have counted separately in *Scorpaena* the two terminal dorsal ray elements which they have enumerated as one ray in *Sebastodes* and other scorpaenids with more extensively branched rays. The anal fin, with similarly little branched rays, has III, 5 rays (the last double), in agreement with the usual counts. If the anal fin were counted by the same method as the dorsal has been, the formula would be III, 6. Hence ichthyologists have followed diverse criteria in counting the dorsal rays in different genera within the one family and in enumerating the dorsal and the anal rays in the same individual. Such confusing discrepancies make it very desirable, as I have repeatedly held, to adopt a single method, universally applicable without dissection or staining, for numerating the soft-rays of the dorsal and the anal fins of all fishes with lepidotrichia. The simplest and best criterion is seemingly that of counting as one ray the last two serial elements that are distinct from the extreme base, whether they be widely, moderately or narrowly separated or even in contact or suturally united (as recommended by Hubbs and Lagler, 1941: 16, fig. 2a).

The principal caudal rays (branched rays plus 2) number 13, as in other specimens of *Scorpaena*. This may well prove to be a generic character, for I find that 14 is the almost invariable number in several species of *Sebastodes* counted. Caudal ray counts have been unduly neglected.

The pectoral rays on each side are 18, or i, 7, x, to distinguish, in line with recent suggestions, the unbranched soft-rays as lower-case roman figures and the branched lepidotrichia in arabic. In *Scorpaena guttata* I find the pectoral ray formula to vary from i to ii, 6 to 8, ix to xi = 18 or 19. Although the pectoral ray formulas are often of systematic significance, the two species of *Scorpaena* under comparison may not differ materially in this respect, for the type figure of *S. mystes* (Jordan, 1895: pl. 52) shows i, 7, xi rays in the left pectoral.

When the misidentified specimen is compared with the type figure of *S. mystes* a marked difference is seen in the dorsal contour of the head. Instead of being nearly straight as it is indicated to be in *mystes* the contour is strongly convex. In consequence the anterior profile is much steeper. When measured with an arm protractor (an instrument that should be in every ichthyologist's kit) the angle between the lower edge of the mandible

and the profile of the snout is about 85°. In *S. guttata* the muzzle angle approximates 90°, but in the type figure of *S. mystes,* making allowance for the slightly opened mouth, it is about 62°.

As seen from in front the interorbital is deeply concave, V-shaped with the sides forming an angle of about 90°. This is true of other young to half-grown specimens of *S. guttata. S. mystes* may have a somewhat flatter interorbital, though the descriptions (Jordan and Evermann, 1898: 1847, 1849) are not adequate in precision ("not very deeply concave" for *guttata;* "not deeply concave" for *mystes*). The least width of the bony interorbital is only half as long as the orbit, not one-half wider than the orbit as stated for *S. mystes* by Jordan and Starks (in Jordan, 1895: 491). This sounds like a trenchant distinction but may be invalid or of only average significance, for age variation was not taken into account. The specimen of *guttata* under study measures only 105 mm. in standard length (5.3 inches over-all) and larger examples have a proportionately wider (and slightly flatter) interorbital. The types of *mystes* ranged to 14 inches in length. The interorbital width in the *guttata* specimen steps 8.4 times in the head, whereas in *S. mystes* this width when divided into the head length gave Meek and Hildebrand (1928: 834, 837) ratios of 5.25 or 5.28 to 8.25 (their specimens of *mystes* ranged in length from 40 to 270 mm.). At comparable sizes *guttata* probably has a narrower and deeper interorbital than *mystes,* but precise determinations of the age variation in each species are needed.

The length of the highest dorsal spine enters the head only 2.25 times. In the elevation of the spinous dorsal *S. guttata* probably differs from *S. mystes,* though the lowness of this fin in the type of *mystes* (3.5 in head) may be due in part at least to age variation, which has not been analyzed.

It is virtually impossible to determine this specimen as *guttata* or as *mystes* by the use of Jordan and Evermann's key (1898: 1840) for that analysis, like many still current, is sadly lacking in accuracy. The first distinction, "lateral line with about 50 scales" in *guttata* versus "about 30 scales in lateral line" in *mystes* is dubious. The scales above, not on the lateral line, of *guttata* are in about 50 rows but the lateral line pores are much fewer (numbering 24 in the specimen under treatment). The count of 30 for *mystes* presumably represented an error or an enumeration of the pores, for Meek and Hildebrand (1928: 837) gave the scale count for that species as 44 to 49. The distinction between the pore and the scale count should be implicit. I note now that I must have meant scales when long ago (Hubbs, 1916: 163) reporting "45 to 55 pores" in *guttata.*

The second key distinction, "no dermal flaps except small ones along the lateral line" in *guttata* and "most of the scales with dermal flaps in *mystes*" is likewise at least largely invalid, for *guttata* has an abundance of such processes over the body, as indeed Jordan and Evermann (1898: 1848) stated in their description of the species. There may well be an average difference in the size of the flaps, for the type figure of *mystes* shows them much larger than they ordinarily are in *guttata.*

The third reputed distinction, "supraorbital tentacles small" in *guttata* and "supraorbital flap large, longer than eye" in *mystes,* is inadequate. In *guttata* this tentacle varies from lacking to almost as long as the orbit. In

mystes, according to Meek and Hildebrand (1928: 837), it is "variously developed or absent and is of no specific value." Variation in the length of the tentacle in *mystes* was also pointed out by Gilbert and Starks (1904: 161). There may be not even an average distinction in this character, but the specimen at hand, with the flap one-half as long as the orbit, might enter either species upon the basis of this character.

The fourth distinction, "axil pale, almost unspotted" in *guttata* versus "axil black and white spots" in *mystes,* is probably of some value though not nearly so sharp as was thus indicated. There may be one or a few small black axillary spots in *guttata.* In *mystes,* according to Meek and Hildebrand, the axil is not black with pale spots, as it usually is in its Atlantic cognate *plumieri,* but rather "is not wholly black, and it usually has only a large black spot." In the example of *guttata* misidentified as "*mistes*" the axillary color like that on the rest of the surface is lost, as the specimen was long on exhibit in the light. It is true that one axil, as well as some areas near the dorsal fin and some spots on the sides, is brownish black, but this color is obviously the remains of a dark mold that once covered the specimen, presumably as the result of the evaporation and weakening of the alcohol. It seems not unlikely that this specimen of *guttata* was misidentified as *mystes* on the supposition that the area of mold in one axil represents the black axil that was described as characteristic of *mystes!*

Although the identification was so obviously in error, it is in a way not surprising, since Fowler (1923: 294) indicated that he spent parts of only two days at Scripps Institution getting the numerous "La Jolla" records that he listed. Perhaps he merely jotted down the misidentification of one specimen of *Scorpaena* as *S. mystes* and failed to determine that this fish bears no locality data and that it is an example of *S. guttata.*

This little story leads to a conclusion of limited concern and to a moral of much wider application. The conclusion, suggested by the first part of the title, is that the tropical fish species *Scorpaena mystes* has been recorded in error as from California. The moral, associated with the second part of the title, is that much greater precision and care are urgent needs in ichthyological research and publication.

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Contribution No. 263

Photograph by Paul Williams

FRANCIS B. SUMNER

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Francis B. Sumner [1]
1874 - 1945

A LEADING American zoologist, many of whose researches dealt with and shed clear light on the biology of fishes, passed away quietly on September 6, at La Jolla, California. There is little need to report the life story of FRANCIS BERTODY SUMNER, Professor Emeritus of Biology at the Scripps Institution of Oceanography of the University of California. He himself told the tale in a fascinating autobiography, "The Life History of an American Naturalist," which very happily came off the Jacques Cattell Press just in time to be appreciated by the author.

It is imperative to note, however, that, in some respects, this book presents a picture of "F.B." which his close friends would have resented, had it been written by another person. A remarkable combination of modesty, reticence and individuality, coupled with an allocation of truth far above all sentiment and tradition, led him to an underevaluation of his own high achievements and to an imperfect representation of his own fine personality. Election to such honors as the Vice-Presidency of the A.A.A.S. and to membership in the American Philosophical Society and the National Academy of Sciences gave some measure of his eminence, as this was appreciated by his colleagues. His transcendent intellectual courage and sincerity, his discerning wisdom and keen wit, forced respect among all acquaintances and endeared him to his intimate friends. Far from being an academic recluse Sumner was charged with social consciousness. He took an active part in nature-preservation and birth-control movements, which to him were phases of a single problem. He vigorously combatted the "boosters" and the anti-vivisectionists. He was a fearless champion of the minority.

Throughout his long scientific career Sumner courageously attacked problems that others had avoided, either because the tasks were of too forbidding magnitude or because the researches were not in line with the current trend or fad of biological thought. His liberal, free-thinking mind led him to favor or at least to investigate open-mindedly such unpopular ideas as the inheritance of acquired characters and the non-particulate inheritance of "normal" characters—until the weight of evidence from his own impartial research finally forced him to accept the conventional viewpoint. His perplexed leaning toward "extrasensory perception" was never wholly abandon d, though his own limited studies in this field gave negative results. Keynotes of all his diverse researches were rigorous intellectual honesty, intense self-criticism, extreme thoroughness and precision. Each problem was rounded out and concluded before another, likely very different, was undertaken.

Sumner's name will probably remain most closely and most favorably associated with his longest research, the brilliant analysis of speciation in mice of the genus *Peromyscus,* but most of his separate studies were conducted on fishes. He was not primarily an ichthyologist, for his problems were those of general biology, but he used fishes as subjects and he did his

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[1] Contributions from the Scripps Institution of Oceanography of the University of California, New Series No. 263.

work so competently, that he ranks as one of the outstanding contributors to general ichthyology. His first paper, with Bashford Dean, dealt with the spawning of a brook lamprey. His doctoral thesis at Columbia, on "Kupffer's Vesicle and Its Relation to Gastrulation and Concrescence," involved some pioneer experimentation. His early study of the physiological adaptation of fishes to changes in salinity was significant, though the methods of a rising clique of physiologists were avoided. A brilliant research on color adaptation in flounders opened a new field. Biological surveys of the Woods Hole region and of San Francisco Bay, which then intervened, proved Sumner to be a competent field naturalist as well as an able experimentalist.

On the discontinuance of the *Peromyscus* project Sumner returned to fish biology, to make very significant contributions on the mechanism of color change. Temperature and respiratory adaptations were then thoroughly studied in the laboratory and in hot springs. He carried out the most conclusive tests ever made of the survival value of individual color adaptations. Quantitative studies of the long-period changes in the amounts of melanin, carotenoids and guanine in the skins of fishes, under different optic stimuli, are acclaimed for their originality, precision and significance. The recent successful conclusion of these experiments proved that Sumner maintained to the end of his research career an ability to overcome such great obstacles as inherent technical difficulties and a limited training in biochemistry.

These final researches were completed and published. The last in a stimulating series of essays, this one entitled "A Biologist Reflects upon Old Age and Death," had appeared. "The Life History of an American Naturalist" had just come out. Social and political movements dear to his heart had come to fruition or to some promise of achievement. Peace had returned to the world. Keenness of mind had persisted and happy relations with family and friends retained. Could death have been better timed?—Carl L. Hubbs, *Scripps Institution of Oceanography, University of California, La Jolla, California.*

Contribution No. 264

Reprinted from SCIENCE, October 5, 1945, Vol. 102, No. 2649, pages 344–346.

FRANCIS BERTODY SUMNER[1]

August 1, 1874–September 6, 1945

PROFESSOR SUMNER'S interests were primarily those of a naturalist; he is best known scientifically for his experimental studies on the nature and inheritance of adaptive variations as the key to an understanding of the problem of organic evolution. These studies have been widely recognized as being of exceptional significance. To him biology is also indebted for the first experimental proof of the origin by mutation of new varieties in any wild species of mammal and the Mendelian inheritance of their characteristics. At the time of his death he had been connected with the Scripps Institution for Biological Research (later the Scripps Institution of Oceanography) of the University of California for thirty-two years, having reached the retiring age of seventy the preceding year. He is survived by his widow, two daughters and a son.

Although he was born in Connecticut, his boyhood was spent first in Oakland, California, then in Colorado Springs and later in Minneapolis. He graduated from the University of Minnesota with the degree of B.S. at the age of twenty, in 1894. It was through his association with Minnesota's Professor Henry F. Nachtrieb that young Sumner was influenced to undertake zoology as a life career. His studies were interrupted by ill health for a year, after which they were resumed in the Graduate School of Columbia University. Here he had the guidance of three of the country's leading zoologists, Professors Edmund B. Wilson, Henry F. Osborn and Bashford

[1] Contributions from the Scripps Institution of Oceanography of the University of California, New Series No. 264.

Dean, although he states in his autobiography that his work with Professor James McKeen Cattell was even more inspiring. In the summer of 1899 Sumner joined an expedition sent to the Egyptian Sudan under the auspices of Columbia University in the hope of securing material for a study of the embryology of the lungfish *Polypterus,* then purported to be a possible ancestor of land-living vertebrates. The expedition was unsuccessful, however, and one of the members died.

For two years previous to receiving the Ph.D. degree from Columbia, in 1901, Sumner taught an undergraduate course in "natural history" at the College of the City of New York. In lieu of the offer of any position elsewhere, this to him irksome job was continued for an additional three years. This experience convinced him that he did not have the aptitude for undergraduate teaching and he decided that his best chance for a successful career lay in some field of biological research. He found such an opportunity in connection with his duties as director of the U. S. Fish Commission laboratory at Woods Hole, 1903 to 1911. Here he began his studies on the relations of heredity and environment in mice. These studies, with some interruptions, constituted his chief problem for twenty-seven years. Other work at Woods Hole, by himself and several associates, consisted of an extensive biological survey of the adjacent seas and seacoasts. Then during the two years 1911 to 1913 he served as naturalist on the U.S.F.C. Steamer *Albatross* in a survey of the physical and biological conditions of San Francisco Bay.

The welcome opportunity of resuming his experimental studies on mice was then offered at the Scripps Institution. To these studies he devoted seventeen years (1913–1930) of intensive effort. This involved the collection of differently colored geographic races or subspecies of the genus Peromyscus at many locali-

ties—from the humid and semi-desert regions of the Pacific coast, the mountains and inland deserts, the alluvial valleys and extending to the white sandy shores of the Gulf of Mexico. These different types were then placed in adjacent compartments under identical environmental conditions at La Jolla. They and their progeny were bred for four to twelve generations. About 2,300 individuals were analyzed in the greatest detail. At the present time it should be needless to add that the progeny showed no heritable deviations as the result of their changed environment. From these stocks, however, Sumner succeeded in obtaining evidence which proved for the first time in any wild species of mammal that spontaneous mutations of large extent as well as minute variations in color patterns were transmitted as single or multiple Mendelian factors. The evidence clearly indicated that this was the mechanism responsible for the origin of geographic races and presumably for specific differentiation and evolution.

The results of these studies were published in six papers covering 280 pages, including one of 106 pages in the Bibliographia Genetica (vol. 9, 1932). This substantial support to the theory of organic evolution brought Sumner much distinction, as witnessed by his election to the National Academy of Sciences, the American Philosophical Society and the Philadelphia Academy of Sciences.

Sumner's second most important contribution to biological theory was his ingenious experiments substantiating the reality of adaptive coloration in the selective survival of individuals and hence, by inference, in evolution. His more recent studies include morphological and chemical analyses of the changes in the pigmentation of fishes subjected to different conditions of lighting. Numerous other papers on the embryology and physiology of fishes show the same meticulous care in devising and executing his experi-

ments and in the strictly impartial analysis and evaluation of the results obtained. Such work will not have to be repeated.

It may be of interest to note that Sumner began his studies on heredity in mice in the expectation of finding evidence in support of the Lamarckian doctrine, only to become finally convinced by the results that such an hypothesis is untenable. In addition to his strictly biological reports he published a considerable number of papers dealing with various sociological, psychological and philosophical problems, including preservation of natural wild-life areas, in which he always took a lively interest. Only a short time before his death he had the satisfaction of seeing in print the last of his writings. Among these was his autobiography entitled "The Life History of an American Naturalist" and a philosophical discussion of old age and death.

In addition to the scientific societies already mentioned, Sumner was a member of many local and national societies devoted to the various subdivisions of biology. Personally he was a man of distinctly superior intellect, kindly and unostentatious on all occasions but fearlessly honest and always ready to champion the cause of the minority. Those who knew him will miss a friendly and always intellectually stimulating association.

Wesley R. Coe

Contribution No. 265

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THE ROLE OF BACTERIA IN THE FORMATION AND TRANSFORMATION OF PETROLEUM HYDROCARBONS[1,2]

By Dr. CLAUDE E. ZOBELL

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ETROLEUM is a complex mixture of gaseous, liquid solid hydrocarbons. Besides the uncounted hun- s of hydrocarbons composing petroleum, there are erous compounds of hydrogen and carbon which ain oxygen, nitrogen, phosphorus or sulfur. Pe- ums from different oil fields differ widely in ical composition and in physical properties. e crude oils such as those from the Bradford, sylvania, sands, for example, are clear amber- ed, free-flowing fluids, while others, exemplified a Brea, California, crudes, are coal black, viscous The density of petroleums ranges from a spe- gravity of 0.65 (certain crudes from the Baku in Russia) to somewhat more than 1.00 for oil Athabaska (Alberta, Canada) tar sands. The e in the chemical composition of petroleums is as ws:

Carbon	82.2 to 87.1 per cent.
Hydrogen	11.7 to 14.7 " "
Sulfur	0.1 to 5.5 " "
Nitrogen	0.1 to 1.5 " "
Oxygen	0.1 to 4.5 " "
Minerals	0.1 to 1.2 " "

hydrocarbons in various petroleums may con- predominantly of either (1) aliphatic compounds e paraffin series, (2) aromatic compounds of the ene series or (3) naphthenic compounds of the methylene or cyclo-paraffin series. Likewise, d in various crude oils are small quantities of acids, phenols, naphthenic acids, resinous com- ds, asphaltenes, mercaptans, thiophenes, sulfones, xides, sulfonic acids, organic sulfides, pyridines, olenes and other compounds. So complex are oleums and so labile are some of their constituents no crude oil has ever been completely analyzed. view of the ever-increasing importance of petro- and its myriads of products to our mechanized and martialized civilization, it seems anomalous that our knowledge of what petroleum is and how it is formed is still so woefully wanting. Petroleum geologists have been so successful in finding subterranean deposits and the industry has been so efficient in providing almost any required amount of amazingly low-cost petroleum products that no one has been too much concerned about what petroleum is or how it was formed. The time has arrived, though, when more knowledge of petroleum and better discovery methods are urgently needed to maintain the supply of low-cost oil. Detailed information on the origin of oil may provide clues to the location of undiscovered petroleum deposits, and such information may affect the economy of exploiting them.

There are almost as many theories regarding the origin of oil as there are students of the subject. Some few still recite the conditions whereby petroleum may have had an inorganic or cosmic origin, but most petroleum geologists hold that "rock" oil had an organic origin. Supporting the organic theory are the nitrogen content of oil, its optical activity, the presence of pigments of the porphyrin type, and the association of oil with marine sediments containing plant or animal fossils. There are widely divergent views regarding the mode of transformation of organic matter into crude oil, but it is generally agreed that (1) the temperature of formation was probably less than 150° C. and it may have been no higher than 30° to 80° C., (2) the pressure of formation was relatively low, (3) the oil was formed not far from the places where it is now found, and (4) it was formed primarily, if not exclusively, in marine environments. Either physical, chemical or biological agencies may have contributed to the formation of oil.

It is not the purpose of this paper to elaborate the theories of petroleum genesis, but rather to discuss the possible part played by bacteria in the formation and transformation of petroleum hydrocarbons. Assuming that the organic remains of plants and animals constitute the mother substance of petroleum, there are several ways in which the biochemical activities

nnual William Conger Morgan Memorial Lecture ered before Alpha Kappa Chapter of Phi Lambda on and the department of chemistry, University of ornia at Los Angeles, April 25, 1945.

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of bacteria and allied microorganisms could be instrumental in the conversion.

Field and laboratory observations during the last decade have established that a biochemically versatile bacterial flora is associated with marine sediments, both recent and ancient. These bacteria or their enzymes (organic catalysts) could be functional in geological environments simulating those in which oil is found and in environments where oil is believed to be formed. Large populations of living bacteria are found in bottom deposits from the floor of the ocean and in reservoir fluids from oil wells. Conclusive proof is still lacking that bacteria are physiologically active in subterranean deposits of brine or oil, but bacteria are unquestionably functional in recent marine sediments to the greatest depths sampled, around 25 feet. Thousands of viable bacteria per gram were recovered from bottom deposits collected at depths exceeding 20 feet below the sea floor. Extrapolating the curve for the vertical distribution of bacteria in recent marine sediments suggests that the lower limits of the biosphere in sedimentary materials would be limited primarily by increasing temperatures at greater depths.

The greatest depth from which samples of sedimentary material have been collected aseptically for bacteriological analysis is 1,560 feet. Cores of limestone impregnated with anhydrite, sulfur and traces of organic matter taken from this depth were found to contain living bacteria capable of propagation in such material. Numerous bacteria are often found in oil coming from depths of several thousand feet, but it is not known whether these are indigenous species or if they are adventitious species introduced after the well was drilled. Nevertheless, the recovery of numerous bacteria years after the well was drilled indicates that they are reproducing in the formation.

From petroliferous sediments have been recovered bacteria, some of which can grow at temperatures as low as 0° C. and others which are physiologically active at temperatures as high as 85° C. The bacteria are not injured by hydrostatic pressures up to 150,000 pounds per square inch, a pressure which is approximately ten times that occurring five miles below the surface of the earth. Some of the bacteria thrive in low salinity water while others grow well in salt-saturated brines. From these observations it is concluded that neither salinity, hydrostatic pressure nor temperatures up to at least 85° C. can be expected to prevent bacterial activity in petroliferous environments.

Most of the bacteria are facultative anaerobes. They attack nearly all kinds of organic matter. In highly reducing environments bacteria tend to convert the organic remains of plants and animal substances which are more petroleum-like. Thi do by splitting oxygen, nitrogen, sulfur and phorus from various organic compounds. T illustrated by the data given in Table 1 on the a proximate chemical composition of the organi tent of sediments of increasing antiquity.

TABLE 1

Type of material	Carbon Per cent.	Hydrogen Per cent.	Oxygen Per cent.	Nit Per
Marine sapropel	52	6	30	
Recent sediments . .	58	7	24	
Ancient sediments ..	73	9	14	
Crude oil	85	13	0.5	

Sapropel consists largely of the recently dep remains of marine plants and animals. A larg of it is decomposed prior to burial. The organi tent of now exposed ancient sediment is less the organic content of recent sediments. Th organic matter has probably been oxidized to dioxide and water. There is no proof that ba are responsible for the changes in the quantit quality of the organic content of sedimentary ma but the occurrence of bacteria in the sediments are potentially capable of such transformati highly significant. Similar reductions in the quantity and in the oxygen, nitrogen, sulfur and phorus content of organic matter incubated ana cally for a few months have been observed laboratory where no such changes occurred in controls. Several of the mechanisms are well whereby bacteria deoxygenate certain kinds ganic matter (decarboxylation), reduce its ni content (ammonification) or remove sulfur (hy sulfide production).

While it is not to be implied from the afo tioned laboratory experiments that bacteria p petroleum from organic matter independent of agencies, it is significant that the bacterial for of hydrocarbons has been demonstrated. In a series of experiments 34 mgm of ether-solubl saponifiable, oil-like material was recovered f culture enriched with 1.2 grams of caproic acid only carbon source. Determinations of the refr index, bi-refringence, optical activity and carbo hydrogen content of this oil-like material ind that it consisted largely of normal paraffins ra from $C_{20}H_{42}$ to $C_{25}H_{52}$. In other extracts fro terial cultures was found a material indistingui from the ceresin waxes of crude oil. Repetiti the experiment have shown that certain sulfate- ing bacteria isolated from petroliferous sed produce small quantities of oil-like extracts

, propionic, butyric, capric, stearic and lactic
Though not proposed as an answer to the
of oil, these experiments establish that sulfate-
ing bacteria can convert certain kinds of natu-
occurring organic matter into petroleum hydro-
ns under environmental conditions resembling
in which petroleum is believed to have been
ed.

e evolution of methane during the bacterial fer-
tion of organic matter is common knowledge.
bly ethane and propane in much smaller quan-
are produced along with the methane. The
rial production of carotene, leprotene, flavorho-
nd other complex pigmented hydrocarbons has
reported. The liberation of benzene from the
rial decomposition of the amino acid tyrosine has
een reported. Theoretically other aromatic hy-
rbons of the benzene series could result from
rial decomposition of organic materials contain-
arbon-ring components.

tain theories of petroleum formation require the
us evolution of hydrogen. As is pointed out,
h, by a leading petroleum geologist late in 1942,
use we have uniformly failed in the past to find
equisite hydrogen within the earth's crust, the
y remains unproved." Looking into the little
red microbiological realms for an explanation,
nd that the anaerobic fermentation of organic
r may result in the liberation of appreciable
ities of hydrogen. In experiments conducted
e S.I.O. laboratories recently, it has been ob-
d that as much as 60 per cent. of the gas (by
e) resulting from the fermentation of glycerol
arine anaerobes consisted of hydrogen. Large
ities of hydrogen are also liberated from cellu-
nd proteinaceous substrates. In the presence
her types of bacteria no free hydrogen may
r because (1) it may be activated to unite with
n dioxide with the production of methane:

$$CO_2 + 4H_2 = CH_4 + 2H_2O$$

ertain bacteria may cause the hydrogen to reduce
es to hydrogen sulfide:

$$SO_4^{--} + 5H_2O = H_2S + 4H_2O$$

) bacteria may actuate the hydrogenation of
urated organic compounds. All three reactions
nown to be catalyzed by anaerobic bacteria which
in marine sediments. Consequently, in such
e sediments one would expect to find the reduc-
roducts (methane, hydrogen sulfide or saturated
carbons) rather than free hydrogen. It may
nificant in this regard that unsaturated com-
ls are not found in petroleum.

ny kinds of bacteria provoke the direct transfer
drogen from one compound to another. Pos-
sibly it is by such a mechanism that lipoclastic anaerobes have demonstrated tendencies toward the reduction and the decarboxylation of fatty acids.

Hydrogen sulfide, which is produced in large quantities by sulfate-reducing and protein-decomposing bacteria, may play a role in the reduction of organic matter to hydrocarbons. The following is a hypothetical example of a reaction which is thermodynamically possible in a highly reducing environment:

$$C_6H_{12}O_6 + 7H_2S = C_6H_{14} + 6H_2O + 7S$$

Some such reaction may account for the observed diminution of the sulfide content in a closed system of anaerobes growing on carbohydrates and proteins. Bacterially produced hydrogen sulfide may favor petroleum formation by creating reducing conditions.

Reducing conditions promote the formation and favor the preservation of petroleum hydrocarbons. The oxidation-reduction potential of marine bottom deposits is as low as $E_h - 0.2$ to -0.5 volts in areas where there is considerable deposition of organic matter. Measurements on profile series show that the sediments become more reducing from the surface downward to a depth of several feet, where the oxidation-reduction potential is uniformly low. Oil-bearing sediments are generally highly reducing, a condition for which bacterial activity may be largely responsible. It has been demonstrated in the laboratory that raw cultures of bacteria taken from marine sediments are able to create in simulated source sediments oxidation-reduction potentials more reducing than $E_h - 0.5$ volt.

Perhaps one of the most important functions of bacteria in the origin of oil is the desorption or release of oil from sedimentary materials. There are several mechanisms by which bacteria liberate oil from oil-bearing sediments. One of the most obvious mechanisms is the dissolution of carbonates by carbonic and organic acids produced by bacteria. When limestone, dolomite or other calcareous materials are dissolved, the oil associated therewith is liberated, and at the same time void spaces or channels are formed which provide for the migration or accumulation of oil. Carbon dioxide produced by bacteria either as a normal product of respiration or from the dissolution of carbonates tends to decrease the viscosity of oil, thereby promoting the movement or flow of oil. By increasing the internal gas pressure, carbon dioxide produced by bacteria *in situ* tends to drive oil from dead-end pockets and through interstitial spaces.

Certain thigmotactic bacteria release oil from non-calcareous sediments. By virtue of the affinity of such bacteria for solid surfaces on which they grow, oil is crowded off. Some of the bacteria produce detergents or surface-active substances which liberate

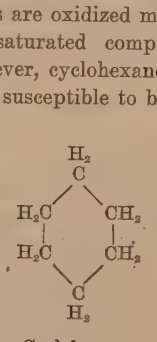
oil from solid surfaces. "Light ends" released by any of the aforementioned mechanisms dissolve heavier hydrocarbons and promote the flow of oil. As will be elaborated below, some bacteria tend to decrease the density of crude oil, probably by splitting methane or other simple hydrocarbons from more complex molecules. It is believed that the action of bacteria in past geological ages has played an important part in the migration and accumulation of petroleum. Whether the oil is still locked in shales, tar sands or other oil-bearing materials or is in a fairly free-flowing state in subterranean structures, may have been determined largely by bacterial activity. The nature of the latter would be determined by the physiological types of bacteria which happened to be present and the prevailing environmental conditions.

The release of oil from plants is another function attributed to bacteria. Most plants synthesize hydrocarbons to some extent, and some, such as the rubber tree, guayule plant, Russian dandelion, candelilla plant and milkweed, produce appreciable amounts of hydrocarbons. The selective decomposition of the plant proteins and carbohydrates following the death of the plant may release the hydrocarbons for eventual accumulation in sediments. Of course, whether the hydrocarbons also will be destroyed by bacteria will depend upon the types of bacteria present and the environmental conditions.

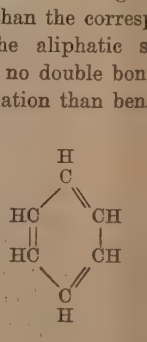
Although generally regarded as biologically inert, most kinds of petroleum hydrocarbons ranging from simple gases to complex solids are susceptible to oxidation by bacteria under certain conditions. Methane, petroleum ether, gasoline, kerosene, lubricating oil, paraffin wax, tars, benzene, xylene, anthracene, naphthalene, mineral oil and cyclohexane are among the common hydrocarbons which are attacked by bacteria. Half a hundred species of microorganisms representing more than a dozen different genera have been shown to utilize one or more kinds of hydrocarbons. Such microorganisms appear to be quite widely distributed in marine sediments. They are particularly abundant in the soil around tank farms, oil wells, leaky gas mains and elsewhere where petroleum or its products are spilled.

Evidence for the microbial utilization of hydrocarbons has been obtained by demonstrating the growth of bacteria in a medium which contains no carbon or energy source except pure hydrocarbons, by measuring oxygen consumption and carbon dioxide production in such a medium, and by observing changes in the hydrocarbons. Since most hydrocarbons are virtually insoluble in water, it is necessary to disperse them in order to provide for their ready attack by bacteria. Some degree of success has been enjoyed by emulsifying the hydrocarbons, but the best r have been obtained by dispersing the hydroca adsorbed on solid surfaces such as asbestos f glass wool, silica sand or diatomaceous earth. the exception of one anaerobic organism, all k bacteria which oxidize hydrocarbons require access to atmospheric oxygen. Representativ the following genera have been credited with the ity to oxidize hydrocarbons: *Pseudomonas, Mic cus, Mycobacterium, Actinomyces, Bacillus, terium, Corynebacterium, Sarcina, Serratia, S lum, Aspergillus, Penicillium, Monilia* and *M monospora.*

Although there is a high degree of specifici the types of hydrocarbons attacked by indiv microbial species, certain tentative generaliza can be made. These generalizations are based observations on the behavior of enrichment cu grown in the presence of about a hundred pure h carbons and a score of "narrow cuts" or refinery ucts. As a rule, aliphatic or paraffinic compo are oxidized more readily than corresponding matic or naphthenic compounds. Long-chain h carbons are more susceptible to bacterial oxid than those of shorter chain length. For exa when similarly dispersed in mineral solutions, pa wax is utilized more readily than lubricating Then follows kerosene, gasoline, low-boiling- petroleum ether and natural gas. There are rela few organisms which can oxidize methane (and it only with difficulty. Oxidized with pro sively increasing ease are propane (C_3H_8), h (C_6H_{14}), octane (C_8H_{18}), decane ($C_{10}H_{22}$), he cane ($C_{16}H_{34}$) and dicetyl ($C_{32}H_{66}$). Branched hydrocarbons or iso-compounds are oxidized by teria more readily than normal or straight homologs. Unsaturated compounds containing d bonds are oxidized more readily than the corres ing saturated compounds in the aliphatic s However, cyclohexane, which has no double bon more susceptible to bacterial oxidation than ben



Cyclohexane



Benzene

It may be of interest to point out in passing rubber hydrocarbons, both natural and synthetic attacked by a large number of microorganisms.

ural rubber or caoutchouc, which has the compo-
on $(C_5H_8)_n$, is more susceptible to microbial oxi-
ion than compounded rubber products. In the
ence of inhibitors, buna-N, buna-S and butyl rub-
s are all readily attacked by bacteria when dis-
sed in appropriate mineral solutions. Thiokols
B and FA, which differ markedly in chemical
position from other synthetic rubbers, are rela-
ly resistant to microbial attack.

Hydrocarbon-oxidizing bacteria may be of consid-
ble importance in the petroleum picture: (1) Such
anisms may prevent the accumulation of oil in
environment except where conditions are inimical
their activity. Thus in seeking the origin of oil
should look for factors which inhibit the activity
hydrocarbon-oxidizing microorganisms. Some of
factors which are known to be inhibitory are
rogen sulfide, low oxidation-reduction potentials
certain heavy metals.

2) There is some evidence that hydrocarbon-
dizing bacteria may alter the properties of crude
by attacking preferentially long chains or branched
ins, by splitting methane and perhaps other simple
rocarbons from more complex compounds, or by
acking preferentially compounds containing oxy-
, nitrogen or sulfur. A decrease in the density
a small sample of crude tar from 1.02 to 0.94
ing six months' incubation has been shown to be
to the action of bacteria.

3) The rapid disappearance of oil pollution in
erways, around refineries, pipe-line leaks, oil seep-
s, along beaches where there is drilling, and else-
ere where oil is spilled in water or on the soil is
eved to be due largely to the activity of hydro-
bon-oxidizing bacteria. This seems to be Nature's
of "pulling the chain" for the disposal of oil
ch otherwise would pollute fields and waterways.

4) Hydrocarbon-oxidizing bacteria may contrib-
to the formation of "paraffin earth" which is quite
monly found in surface soil overlying subter-
ean deposits of petroleum. Certain samples of
alled "paraffin earth" have been found to contain
ge numbers of hydrocarbon-oxidizing bacteria or
r refractory remains.

5) Large numbers of bacteria which oxidize vola-
hydrocarbons, including ethane, propane and
ane, are found in surface soil surrounding or over-
g oil fields. The demonstration of these bacteria
heir fossil remains in surface soil in definite dis-
ution patterns is the basis of so-called "geomicro-
ogical" prospecting methods. Although nature
erally hides her treasures well, she usually leaves
lue, which in this case may be the fossil remains
hydrocarbon-oxidizing bacteria. The perfection
of a technique for the rapid identification of such fossils in the field may provide another tool to aid in the search for oil.

(6) The whimsical behavior of hydrocarbon-oxidizing bacteria sometimes results in confusion in the search for oil by "soil analysis" methods of prospecting. Volatile hydrocarbons in soil samples collected for analysis may be destroyed quantitatively within a few hours by bacteria, if conditions are conducive to the activity of such bacteria, resulting in negative or anomalous findings. The failure of various workers to find petroleum hydrocarbons in recent sediments may be due to the increased activity of hydrocarbon-oxidizing bacteria following the collection, transportation and storage of the samples.

(7) Microorganisms which attack hydrocarbons are sometimes instrumental in causing undesirable changes in petroleum products stored over water. The discoloration of refinery products and the formation of gummy substances have been traced to the activity of hydrocarbon-oxidizing bacteria. This also applies to observed decreases in the octane rating of aviation gasolines which in certain emergencies and experimentally have been stored over water. The action on aviation gasolines is threefold: (a) Branched-chain hydrocarbons which have the highest anti-knock characteristic are preferentially attacked with the liberation of some methane, (b) microbially produced sulfides precipitate tetraethyl lead, and (c) peroxides produced by the bacteria catalyze the deterioration of tetraethyl lead.

(8) There is a report in the literature which ascribes an explosion of a kerosene tank to the production of a mixture of methane and hydrogen from the bacterial decomposition of kerosene in water storage.

(9) The growth of hydrocarbon-oxidizing bacteria in medicinal and pharmaceutical preparations having hydrocarbon bases has resulted in discolored and otherwise altered products. Allergies have been traced to the use of such products. Cooling oils have also been unfavorably affected by the profuse growth of hydrocarbon-oxidizing bacteria.

Little is known regarding the end-products which result from the bacterial utilization of hydrocarbons, except that carbon dioxide and bacterial protoplasm are always produced. There are reports in the literature on the production of methane, hydrogen, ketones, aldehydes, alcohols and organic acids. The products of metabolism will depend upon the bacterial species, the hydrocarbons and the experimental conditions. The observation that fatty acids result from the bacterial oxidation of petroleum hydrocarbons suggests exploring the possibilities of using microbial catalysts

to convert hydrocarbons into much needed edible fatty acids. More extensive and intensive studies on the products of hydrocarbon utilization can be expected to yield interesting information on bacterial physiology.

In conclusion and to clarify my own views on the subject, it should be emphasized that while bacteria probably play an important role in the formation and transformation of petroleum, geological, geophysical and geochemical factors are also believed to be of importance in the origin of oil. The bacterial synthesis of certain petroleum hydrocarbons has been demonstrated, but it seems doubtful if it will ever be practical to produce by bacteria any hydrocarbons except methane on a commercial scale. The fondest hope for the future now entertained is that intensified microbiological studies coupled with other investigations on the origin of oil may eventually provi information which will aid in the discovery of existi pools of petroleum. Geomicrobiological prospecti and refined methods of "soil analysis" may prove be a step in this direction. Microbiological process may find practical applications in the petroleum i dustry, the most promising of which appears to the use of bacteria in the recovery of petroleum fro oil-bearing materials, in certain refinery process and in the disposal of various waste products. Whe ever petroleum or its products are stored in conta with water, the possible effects of hydrocarbon-oxidi ing microorganisms must be taken into account. T multiple effects of bacteria on the formation a transformation of petroleum hydrocarbons is a n frontier of learning which presents a challenge to t petroleum industry and to the microbiologist.

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CALIFORNIA SEAROBIN (*PRIONOTUS STEPHANOPHRYS*), A FISH NEW FOR THE FAUNA OF SOUTHERN CALIFORNIA [1]

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Fishes of the genus *Prionotus,* known as searobins, are common members of the Atlantic Coast fauna of the United States and are not rare on either side of tropical Middle America, but have very seldom been found on the Pacific Coast of the United States. In fact, only one of the several species known from waters to the southward has been recorded on valid grounds from as far north as California, and only two or three specimens seem to have been collected north of the Mexican border. It is therefore of interest to report the first taking in southern California of a specimen of this species, *Prionotus stephanophrys* Lockington (1881, pp. 529-532).

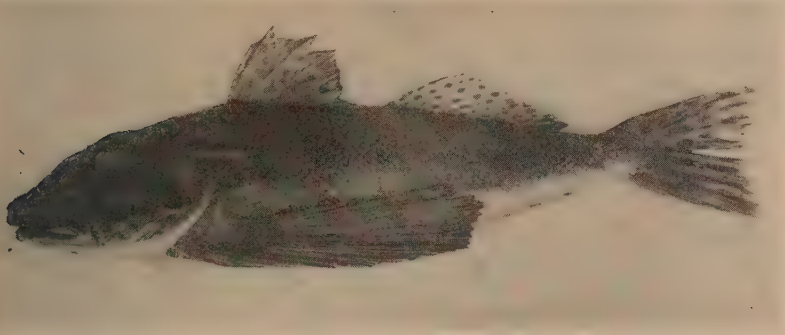

FIG. 62. California searobin, *Prionotus stephanophrys*: a 12⅛-inch specimen, the first to be recorded from Southern California. Photograph by Paul Williams.

Although the species has so seldom been collected in California, the first described or type specimen was taken in October, 1880, in a paranzella trawl "in the tolerably deep water of the region between the rocky islets known as the Farallones, the entrance of San Francisco Bay, and Point Reyes, a rocky promontory some forty miles north of San Francisco." The discription of the species by Jordan and Gilbert (1883, p. 736) and the revisionary treatment by Jordan and Hughes (1886, pp. 329 and 334) were both drawn up on the basis of Lockington's one example (No. 27048, United States National Museum). No further material appears to have been recorded until 1896, when Jordan and Evermann (p. 487) assigned to this form a range in "deep water, off San Francisco, Point Reyes, and Monterey." Presumably "San Francisco" referred to the type speci-

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men and the Point Reyes record was probably based on a specimen (No. 2001) in the fish collection of Stanford University, but no basis has been found to validate the Monterey report.

All subsequent published records for *Prionotus stephanophrys* are for waters south of California. These records need some consideration, since they are surrounded with confusion. The first southern report was by Jordan and Evermann (1898, p. 2161) who added Lower California to the previously assigned range of the species and drew up their description from "Mr. Lockington's type, and from two others collected by the *Albatross* at Station 3041, coast of Lower California." This station was in Magdalena Bay at a depth of 27 fathoms (Townsend, 1901, p. 407), but the two specimens apparently came from *Albatross* Station 3039, just off Magdalena Bay, at a depth of 47 fathoms. According to Dr. Leonard P. Schultz of the United States National Museum, Jordan and Evermann apparently transposed the Lower California stations for two species of *Prionotus,* giving Sta. 3041 for *stephanophrys* instead of Sta. 3039, and Sta. 3039 (wrongly located "in the Gulf of California") in place of 3041 for *quiescens.* The next record for *P. stephanophrys* which I find is that of Ulrey (1929, p. 9), repeated by Cuestra Terron (1932, p. 79), for "Gulf of California," but there seems to have been no basis for this report. Some clerical error was probably involved. Later Breder (1936, pp. 39-40, fig. 13) did report *P. stephanophrys* from "Angelus" [Angeles] and San Francisquito bays on the east coast of Baja California, and also from the west coast of Mexico just north of the Guatemala border. Hiyama's figure of *"Prionotus quiescens,"* which he reports (1937, p. 56, pl. 90, fig. B) to be "common in Gulf of California," seems to represent *P. stephanophrys.*

The validity of these Mexican reports for *P. stephanophrys* are open to some doubt, and the Gulf of California records of *P. quiescens* may all belong with *P. stephanophrys.* Indeed the two nominal species may prove inseparable. Breder's identifications, cited above, were made with some hesitancy, and his figure shows several points of divergence from *P. stephanophrys,* particularly in the almost unspotted first dorsal fin.

It is obvious that a critical revision of the Pacific species of *Prionotus* is much needed. Material for such a study is now rather plentiful, in the fish collections of the New York Zoological Society, American Museum of Natural History, Bingham Oceanographical Collections, United States National Museum, Stanford University, California Academy of Sciences and the Allen Hancock Foundation of the University of Southern California.

The one previous report of a searobin from southern California was probably an error. In "A Check-list of the Fishes of Southern California and Lower California" Ulrey (1929, p. 9) indicated by symbol that *Prionotus gymnostethus* occurs in southern California. No *Prionotus,* however, is mentioned in Ulrey and Greeley's report (1938) on their southern California collections and no specimen of any Pacific species of the genus could be found in examining Ulrey's collection, now in the Allen Hancock Foundation. Nor is any *Prionotus* listed in Barnhart's book on the "Marine Fishes of Southern California" (1936). No evidence whatever could be found to substantiate the inclusion of southern California in the range of *P. gymnostethus.*

To summarize what is known of the distribution of searobins in California, it may be stated that only one species, *Prionotus stephanophrys* Lockington, has been recorded on authentic grounds from the State. Only two California specimens, both collected long ago near Point Reyes, have been located in any of the museums that might be expected to have material from the State. The one other locality record, for Monterey, has not been validated. The same species probably occurs on the outer coast of Baja California and in the Gulf of California, and perhaps in still more southerly waters, but there appears to be no valid record for the occurrence of this or of any other species of *Prionotus* in southern California.

That *Prionotus stephanophrys* does live in southern California may now be affirmed. A specimen 12⅛ inches in overall length was caught in Santa Monica Bay on October 24, 1944, 64 years after the type was trawled near San Francisco. The new specimen was taken on a hand-line by Michael Waxman four to five miles off El Segundo. According to Hydrographic Office charts this locality is at approximately Lat. 33° 53′ N., Long. 118° 30′ 30″ W. Here the depth is indicated as about 30 fathoms and the bottom as of sand and gravel. The example, a female with eggs approaching ripeness, is illustrated on Fig. 62. It is deposited in the Natural History Museum of Stanford University (No. 39788).

Like other searobins this specimen has the upper parts and sides of the head covered by an armature of bony plates ornamented with granulated ridges. These bones, however, are less roughened than in most species of *Prionotus* and the spines of the head are relatively weak. The main part of the blackish pectoral fin is a large flabby structure resembling the "wing" of the distantly related flying gurnard, to which some biologists with free imagination attribute the power of flight. Below this membranous part of the pectoral there are the three separate finger-like rays that are an outstanding feature of the family (Triglidae) in which *Prionotus* is classified.

The southern California example corresponds well with the published descriptions of *P. stephanophrys*. The main discrepancies—a smaller eye and lower ridges and shorter head spines—are attributable to a difference in size, for the new specimen is an adult and those previously described were only half-grown.

For the benefit of ichthyologists who may undertake a critical study of the characters and distribution of *Prionotus stephanophrys* and other Pacific species of the genus, there follows a detailed description of the new specimen, which is the first adult to be described. The figures in parentheses are the proportional measurements expressed in thousandths of the standard length (252 mm.).

The body is moderately robust for a gurnard, with the greatest depth (260) below the middle of the first dorsal base. The dorsal and ventral contours are nearly horizontal along most of the trunk but then converge backward to the rather slender caudal peduncle (depth, 71). The body throughout is slightly compressed, except above the end of the anal base, where it is as wide as deep (greatest width, across scapular spines, 229).

The head is long and massive (length to end of opercular membrane, 390; to end of opercular spine, 384; to occiput, 291). Then depth of the head below the occiput (230) approximates the greatest width across the preopercular spines. The dorsal contour is gently concave from the tip of the snout to a rather prominent hump in front of the eye, thence less steep and slightly convex to the front of the dorsal (the respective angles formed with the mandibular edge are 51° and 23°). As seen from

above the front of the snout is widely truncated but scarcely emarginate. Measured between the centers of radiation on the suborbitals the width of the snout (169) somewhat exceeds the depth (158) below the preocular spine. The snout length (148) enters the head length about 2.6 times. The eye (61) is contained about 2.4 times in the snout; the bony orbit (95), 1.6 times.

The interorbital is broad and nearly flat, though shallowly grooved on either side of the low rounded median ridge. Its least width (57) is a little less than the length of the eye. The edges of the interorbital are deeply concave (width across preocular bony rim, 61; between preocular spines, 78; between edges of crest posteriorly, 90). The width between the occipital spines (94) is a little greater than the distance (87) from the occiput to the dorsal origin. The least distance from the bony orbit to the preorbital edge (63) barely exceeds the length of the eye. The distance from the preopercular ridge to the tip of the opercular spine is 116 thousandths of the standard length.

The head spines are very weakly developed. The lateral margin of the snout is roughened by about 20 tubercular spinelets directed forward. The upper anterior border of the orbit bears indistinct points at the tips of short ridges. The strongest of these points forms the scarcely differentiated preocular spine. The postocular spine has a free projection of less than 1 mm. on one side and of even less on the other side. The edge of the gentle slope in front of the postocular spine has fine, rather indistinct serrations at the ends of tuberculate ridges. Behind the postocular spines the bony margin forms a semicircular indentation and the surface of the head becomes abruptly flatter, but there is no definite transverse groove. There is a rather large bony excrescence at the anterior end of the lateral line a short distance in advance of and slightly below the weak low-lying occipital spine, which does not extend to opposite the dorsal origin.

The suborbital margin is very finely and indistinctly serrated. There is no trace of a spine at the center of radiation on the suborbital. Measured from the suture between the suborbital and the preopercle, the length of the preopercular spine (60) almost equals the length of the eye, but the spine is free for only half its length and its tip does not reach the free margin of the subopercle. The indistinct upper opercular spine is flat and far removed from the opercular margin. The outer edge of the thin opercular bone is nearly semicircular between this spine and the flattish, somewhat upturned main opercular spine, which extends slightly beyond the opercular membrane.

The mouth is rather large, as the upper jaw (163) reaches slightly beyond the vertical from the front of the orbit and measures 2.35 in the head. The proportional length of the mandible is 175. Fine villiform teeth form rather narrow bands with the following maximum widths, expressed in ten-thousandths of the standard length: premaxillary, 102; vomer, 83; palatine, 100; mandible, 91. The vomerine patch is weakly convex. The gill-rakers on the outer arch number 4 above the angle, with only one well developed, and 19 below, becoming rudimentary at about the tenth. Interpolated between the main rakers are small denticulate tubercles. There are seven branchiostegals.

Of the 10 dorsal spines the third and largest is about two-fifths as long as the head. The proportional lengths of the first four spines are: first, 123; second, 137; third, 163; fourth, 155. The others become progressively shorter to the tenth, which is largely imbedded. The front edge of the first spine is finely granulated along the basal half. The soft-rays number 12, with the first one unbranched but articulated. The anal formula is I, i, 9 (the anal formula of *Prionotus* has apparently been misinterpreted; in *P. stephanophrys*, as presumably in the other species, the first of the two unbranched rays is a true though somewhat flexible spine, whereas the second anal ray, like the first ray of the second dorsal, is a paired and articulated though unbranched soft-ray).[2] The proportional lengths of the anal rays are: spine, 42; unbranched soft-ray, 72; first branched ray, 88; fifth and longest branched ray, 98. The caudal fin, which has 12 principal rays (10 branched), is weakly lunate (length of shortest median ray, 189; of longest ray, 231). The main part of the pectoral fin has a very weakly convex posterior edge from the first to the ninth of the 13 rays, of which the first and the last are simple, the others once branched (the lengths of the rays on the right side—the left fin was injured—are as follows: first, 339; seventh and longest, 424; ninth, 420, graduating to the eleventh which is 229). The fin extends to above the base of the sixth anal ray. The tips of the free pectoral rays are scarcely swollen and these rays are graduated in length (219, 190, and 158). The pelvic fin (254) extends three-fourths the distance to the anus.

[2] The morphological and systematic aspects of fin structure in teleosts are discussed in a recent paper (Hubbs, 1944) and will be further considered in forthcoming papers.

The thin, weakly ctenoid and rather poorly imbricated scales are probably characteristic of the species. They are reduced in size on the nape, near the midline of the belly and about the isthmus, but are rather large near the center of the breast and just behind the pelvic fins. Over the pubic bone medically the scales are slightly imbricated, but just in front of each pelvic and over most of the belly they are nonimbricate. A scaleless strip extends from behind the pectoral base to just behind the pelvic base, but the main part of the breast is scaly. The head bears a few scales on the upper part of the subopercle, between the two opercular spines. There are 52 pores in the lateral line.

In formalin the body is rather sharply bicolored. The side above the upper edge of the pectoral fin is warm purplish brown with scattered blackish brown specks and small blotches, but is not barred. The lower side and the ventral surfaces are white. A trace of yellow remains on the under side of the head. Above, the head is scarcely spotted, except for obscure speckling on the upper part of the eye. Both dorsal fins and the caudal are dusky purplish with blackish purple spots. Of the numerous spots on the first dorsal the two that are most conspicuous lie, respectively, between the fourth and the fifth and between the fifth and the sixth spines, but there is no large black blotch in this area. The second dorsal bears conspicuous rounded spots, which do not quite reach the upper margin and mostly lie along the front of the rays. These spots are alignable into three or four rows and indefinitely into about two more rows. The spots on the caudal are less distinct and the submarginal ones are elongated, though not fused to form a band. On the upper lobe the spots comprise about five bars, but those on the lower lobe are much less distinct. The anal and pelvic fins are white, with some sooty color on the rays. When folded the pectoral fin is purplish black, but when spread it is dusky purplish with numerous, irregularly elongated blackish spots.

The taking of this specimen once again illustrates how incomplete is our knowledge of the fish life of the moderate depths along the coast of southern California. It is quite possible that this and some other species being discovered in these waters may prove of some commercial significance, when federal restrictions that now hold down the coastal fisheries may be lifted. It is reported that in 1943 more than 300,000 pounds of searobins were taken in the commercial fisheries of the New England and North Atlantic states.

Acknowledgments

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Contribution No. 268

TRANSPORTATION OF MARINE BEACH SAND BY FLOTATION

BY

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TRANSPORTATION OF MARINE BEACH SAND BY FLOTATION[1]

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ABSTRACT

Floating sand has been abundantly reported from streams, lakes, and estuaries, but its frequent occurrence on marine beaches has received little attention. On beaches, flotation results in transportation for only a few yards, but the selective sorting by size, angularity, and mineralogy of the sand grains may be of some geological interest.

GENERAL

The presence of patches of sand and sometimes even of stones floating on the surface of water has stirred the interest of many observers because of the incongruity of material of high specific gravity floating on a liquid of lower specific gravity. A score of observations have been published in the form of short notes. These reports were summarized by McKelvey (1941) who also gave an excellent discussion of surface tension, the means by which the particles are supported.

Sand may be found floating on water of streams, lakes, estuaries, and marine beaches. Even more often it may be seen floating on street puddles after rains. Of the natural environments, marine beaches fronting the open ocean have been practically neglected in previous reports, though floating sand is commonly present.

MARINE BEACH ENVIRONMENT

Floating sand has been noted by the writer in four different portions of open marine beaches: large ponds on the backslope, tidepools, rills, and at the edge of advancing waves.

Some beaches have a profile such that a crest, which is somewhat above high tide, separates the seaward sloping foreshore from a broad gentle blackslope. At the highest tides, the first wave which washes over the crest of the beach initiates a pond and successive waves increase its area and depth. As the water-line of the pond slowly advances, many of the sand grains at the surface are lifted and floated, and they soon collect in patches. If there is a slight breeze, much of the sand floats to the leeward side of the pond. When the tide falls, the water of the pond filters out through the beach and the floating sand is stranded, largely along the highest water-line on the leeward side.

Floating sand is even more common in the quiet tide pools left by a falling tide between large ripple marks and in scoured areas around rocks. Sand surrounding these pools is thoroughly wetted during high tide before the pools are formed, but on exposure to air the sand grains require only a moment to repel the surface film of water, especially during a sunny day. Many of these sand grains are launched at the water-line when a gust of wind causes a slight change of water-level. Additional grains also may be launched from the surface of slumping portions of the pool walls. Small rills of water draining into the pools from higher parts of the beach sometimes contribute a small load of floating sand. The ease with which sand can be set afloat is illustrated by the fact

[1] Contributions from the Scripps Institution of Oceanography, New Series No. 268.

that if a handful of sand from the bottom of the pool is lifted above the water for a moment and then gently immersed, much of the surface layer floats away. The floating sand soon collects in elongate patches parallel to the water-line (pl. 1, fig. 1). Usually these patches drift toward the middle of the pool and become more or less circular (pl. 1, fig. 2). As the tide falls, the water in the pools seeps out and the patches of sand are stranded on the bottom and sides of the pools, often intact and in distinctive patterns.

Floating sand may also be found in rills of water running down the beach slope. While the rills consist partly of water draining from intergranular spaces, for the most part they return seaward part of the water carried up the beach by waves. On the surface of the water occasional separate sand grains may be seen afloat. So far as the writer can determine, all this floating sand sinks when it reaches the rough water of the next advancing wave. It then is deposited or joins the sand being carried by saltation or in suspension. Since even sharp-crested ripples are usually sufficient to wet and thus to sink floating sand, it is very unlikely that floating sand from rills of an open marine beach ever passes the breaker zone.

An additional type of sand flotation was described for lake beaches by O. F. Evans (1938b) and this is also present on nearly all marine beaches. As a wave advances over a beach, its edge supports and carries a narrow band of floating sand which is deposited as a swash mark when the wave reaches its highest level and then recedes and partly sinks into the beach. Especially evident on marine beaches is a zone where the sand is covered by a very thin but smooth glassy layer of water left by a wave (pl. 1, fig. 3). Just landward of the glassy surface, the sand, though still wet to the touch, presents a dull granular surface, and there the grains apparently have repelled part of their surface film. Because the top of the sand grains is dry only in the zone having a dull granular surface, grains are picked up by advancing waves and swash marks can thus be formed only in that zone. Swash marks are formed rarely, if ever, in the zone having a glassy surface.

PETROGRAPHIC CHARACTERISTICS OF FLOATING SAND

Most published accounts give the size of floating sand as medium, coarse, or very coarse. R. T. C. Evans (1900) reported even stones floating from a marine beach. Floating sand collected from a lake and sieved by O. F. Evans (1938a) proved to be coarser than the beach sand from which it was believed to have been derived. It had a median diameter of 0.50 mm. as compared to 0.33 mm. for the samples collected from the lake beaches, thus indicating some selection. Floating sand collected from a tide-pool (pl. 1, fig. 2), however, had the same median diameter as that from the pool walls, 0.173 mm.

Simonds (1896) and others report that angular grains float much better than round ones. In accordance, flat angular shell fragments and mica flakes are frequent components of floating sand on marine beaches. As explained by Coghill and Anderson (1918), the selection of angular grains results from the fact that it is difficult for the surface or miniscus of the water to pass around the sharp edges of angular grains, and thus they tend to remain at the surface of the water. Moreover, the weight of a grain must not bear too large a ratio to its perimeter because the force of gravity must be balanced by the surface tensions. Therefore, large grains do not float as easily as small ones unless they are more angular or flatter.

Microscopic examination of the floating sand and the wall sand from a tide-pool (pl. 1, fig. 2) revealed the presence of a large suite of light and heavy minerals. In the $\frac{1}{4}$ to $\frac{1}{2}$ mm. size grade, biotite flakes constituted 33.5 per cent of the floating sand and only 5.5 per cent of the wall sand. In the $\frac{1}{8}$ to $\frac{1}{4}$ mm. size grade, biotite amounted to 4.5 and 1.0 per cent respectively. Only a few grains of biotite

PLATE 1

(See opposite page for legend)

were present in smaller size grades. Although much less abundant, chlorite flakes showed the same relationship. Non-flaky minerals had about equal proportions in the floating and the wall sand after biotite and chlorite were subtracted from the mineral count.

Numerous cursory examinations of swash marks showed them to be similar to the floating sand in that biotite is much more abundant than in the source sand.

GEOLOGICAL SIGNIFICANCE

As pointed out by McKelvey (1941) and others, flotation may result in the transport of large quantities of sand in streams, lakes, and estuaries. While a large quantity of sand is also floated in the marine beach environment, it is rarely transported more than a few yards distance. On the beaches, however, flotation does result in some selection as regards grain size, angularity, and mineralogy so that both the floated and the residual sand can differ from the original sand. Floating sand which is stranded as swash mark has been found in consolidated sandstones and it is possible that patches of sand floating in pools and stranded when the pool drained away also may be preserved.

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PLATE 1. Illustrations of floating sand on beach near Scripps Institution of Oceanography, La Jolla, California.

FIG. 1. Elongate patches of sand floating in a tide-pool parallel to the water line. Dark area is shadow of camera held over pool.

FIG. 2. Roughly circular patches of sand floating in a tide-pool.

FIG. 3. Portion of beach after the seaward retreat of a wave to the right. Scale is given by pebbles one and one-half inches in diameter. Note glassy surface at right which is slowly changing to a dull granular surface. Just after the photograph was made a wave advanced to a position diagonally across both glassy and dull granular zones before it retreated seaward. Sand was floated and a swash mark was formed in the dull granular zone but not in the glassy zone.

Contribution No. 270

RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL, 1944, TO APRIL, 1945

H. U. Sverdrup and Staff

(Contribution from the Scripps Institution of Oceanography, New Series, No. 270)

Participation of members of the staff in war work has continued and has been further expanded. The nature of the work is such that as yet no report can be given to the American Geophysical Union.

G. F. McEWEN has completed the revision of certain preliminary basic mathematical tables required for further researches on evaporation and mixing, and a limited number of photostatic copies are on file. The tables are as follows:

(A) Table of e^{-x^2}, carried to six decimal places at intervals of 0.001 within range for x from 0 to 2.50, and of 0.01 within range 2.50 to 3.30.

(B) Table of $\left(\frac{e^{-x^2}}{x}\right)$ and $\int_x^\infty \left(\frac{e^{-x^2}}{x}\right) dx$, carried to six decimal places at intervals of 0.001 within range for x from 0 to 2.50 and of 0.01 within range 2.50 to 3.30.

(C) Table of $P_0(z) = \int_{0.001}^{z} \left[\int_z^\infty \left(\frac{e^{-x^2}}{x}\right) dx\right] dz$, carried to six decimal places at intervals of 0.001 within range for z from 0.001 to 0.500, and of 0.01 within range 0.500 to 3.000.

(Note: $P_0(3)$ differs only one in the sixth place from the limiting value.)

(D) Tables of $\int_x^\infty \left(\frac{e^{-x^2}}{x-c}\right) dx$ and $\int_x^\infty \left[\frac{e^{-x^2}}{x(x-c)}\right] dx$, carried to four decimal places at intervals of 0.05 within range for c from 0 to 3.15 and of 0.01 within range for x from $(c + 0.01)$ to $(c + 0.20)$.

These two integrals, each of which required double-entry tabulation with respect to both x and c for c = 0, were particularly difficult to evaluate and required the formulation of various special devices, depending upon the values of x and c, in order to obtain the required accuracy of four decimals. The range of values probably includes those most likely to be needed in proposed applications to the problems of evaporation and mixing, and covers the field most difficult to compute. Since it was first necessary to compute the integrals

$$\int_x^\infty \left(\frac{e^{-x^2}}{x+c}\right) dx \quad \text{and} \quad \int_x^\infty \left[\frac{e^{-x^2}}{x(x+c)}\right] dx$$

it is the intention to prepare copies of these tabulations as well, in order to save the results for possible use later.

From Table B, as indicated above, Table 2 of McEWEN'S Distribution of temperature and salinity [see 1 of "Reference" at end of paper], can readily be revised as may be required for application to either fresh water, sea water, or the atmosphere.

Preparatory to proposed studies of the vertical distribution of temperature and humidity, attempts have been made to fit empirically certain simple mathematical formulas to data already published. A simple hyperbolic law has been found to apply quite accurately in many cases, this facilitating the computation of gradients and the development of theories of vertical distribution.

In August, 1944, work on the above tabulations was interrupted in order to develop further the solution of the problem of the horizontal dispersion of material from an initial source, circular in form. This problem arose in connection with studies on the distribution of fish eggs and larvae in the ocean. The solution obtained early in 1944 was subject to certain limitations in the range of values and involved an error of about one per cent. Further researches in the problem were

undertaken because of unexpected applications in another field involved in a war project. Importa improvements were worked out in response to an urgent request and a complete solution of greate accuracy was finally obtained. One final step in the solution proved particularly difficult, that of evaluating

$$\int_{x_1}^{x_2} \left(\frac{e^{-x^2}}{\sqrt{a+x}} \right) dx \qquad \text{and} \qquad \int_{x_1}^{x_2} \sqrt{a+x}\ e^{-x^2}\, dx$$

Solutions of these integrals, adapted to theoretical interpretation and to methods of numerical eva ation, have been completed.

In view of the progress made in dealing with the various mathematical problems, apparently separate and disconnected, attention can now be directed mainly toward obtaining unified results with emphasis on the physical aspects required in certain researches on the ocean and atmospher

The usual observations of temperature, salinity, and weather at our six stations on shore and supplementary observations from United States Lighthouse tenders have continued. There were about 1,800 observations of salinity and sea-temperature, and 1,500 observations of wind. Barograph-recording, pyrheliometer-records, and daily observations of humidity and precipitation were continued.

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[1] G. F. McEWEN, Bull. Scripps Inst. Oceanography, 1929, pp. 268-278.

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TRANSFORMATION OF POLAR CONTINENTAL AIR TO POLAR MARITIME AIR

TRANSFORMATION OF POLAR CONTINENTAL AIR TO POLAR MARITIME AIR*

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United States Army Air Forces

(Manuscript Received, May 28, 1945)

ABSTRACT

The changes in the content of heat and water vapor which characterize the transformation of continental-polar air as it moves out over the sea are considered. Computations indicate that these changes can be accounted for by the transfer processes operating at the sea surface. A solution is obtained for the surface air temperature at any phase of the transformation in terms of the initial surface air temperature, the initial lapse rate, the sea-surface temperature, and the distance the air has traveled over the sea. The solution is presented graphically for the use of the forecaster.

Temperatures are computed for ninety-six cases and compared with the observed temperatures.

LIST OF SYMBOLS

C_p specific heat of dry air at constant pressure
C_v specific heat of dry air at constant volume
E evaporation from the sea surface
g acceleration of gravity
h heat content per unit mass of air
H total heat content of a column of air up to a given height
H_0 total heat content of the column at $x = 0$
ΔH change in total heat content
L latent heat of vaporization
M $\dfrac{R}{g\gamma^2(R\Gamma_a + 1)} = 8750$ meters per degree
N $\dfrac{R\Gamma + 1}{R(\Gamma - \Gamma_a)}$
p pressure
p_s surface pressure
P pressure at top of region 2
P' pressure at top of region 3
q specific humidity of the air
q_0 initial value of the specific humidity
Q_h flux of sensible heat from the sea surface
r coefficient of correlation
R gas constant for dry air
t time coordinate
T temperature at a height of 15 meters, called surface air temperature
T_0 initial value of surface air temperature
T' temperature as a function of both x and and z
T_0' temperature as a function of p or z at x
T_P', T_{0P}' temperature at the top of region 2 wh densation is neglected
T_s sea-surface temperature
u wind velocity at 15 meters
u' wind velocity at any height
v $T/\bar{T}_s$
v_0 $T_0/\bar{T}_s$
W total water-vapor content of a column given level
x horizontal coordinate
X length of column trajectory over water
z vertical coordinate
Z height of top of region 2
Z' height of top of region 3
α' specific volume as a function of x and z or
γ^2 resistance coefficient
Γ, Γ_a initial and dry adiabatic lapse rates
θ potential temperature at a height of 15
θ' potential temperature as a function of z
θ_s potential temperature of sea surface
μ_e coefficient of eddy viscosity, conductiv fusion of water vapor
ρ density of the air at a height of 15 mete
ρ' air density as a function of x and z or x
τ stress
ϕ dynamic height

1. Introduction. Changes in the physical characteristics of an air mass are effected by the surface over which it passes, so that the forecasting of transformations is in part a problem in evaluating the processes in the lower layers of the atmosp many weather situations the modifications of mass brought about by these processes proceed a rate that the effects of radiation are negli

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ison. Whenever this is true and the effect of the r processes can be determined quantitatively, ulting changes in the air mass can be accurately ed.

transformation of *cP* to *mP* air should lend o theoretical treatment because transfers from surface of heat and water vapor take place so that radiation can be neglected. Therefore, extreme instability causes turbulent motion is much more intense than in the case of ent equilibrium, the theory of turbulence can be directly to the problem of transformation of *P* air.

. Sverdrup believed that it should be possible cast the various phases in the above trans- on by computing the evaporation and the flux ible heat from the sea surface and evaluating fect in changing the content of heat and water in a moving column of air. Assuming that s in heat content brought about by radiation gligible, he designed an empirical study to test ic assumption: that the actual heat and water- uxes under the conditions of extreme instability ower layers, which characterize the transforma- *cP* to *mP*, are not substantially larger than the ical fluxes computed on the assumption of ent equilibrium.

problem was discussed by H. U. Sverdrup in ourses in maritime meteorology given for officers Army Air Forces at the Scripps Institution of graphy and the University of California at Los s in 1943–1944. The work with the data was out by the officers in the courses. Well-marked aks of polar air from 1935 through 1938 were . The data available were surface maps (*Daily ic Series—Historical Weather Maps—Northern phere Sea Level*, published under the auspices of nt Meteorological Committee) and soundings even stations in the eastern United States.

rder to determine the observed changes in the as necessary to compare the soundings charac- the air over the sea and the same air over the he lower part of the soundings which charac- the air over the sea was obtained from ship . The pressure and temperature reported by the re used and a relative humidity of 80 per cent sumed. An examination of the *U. S. Weather Climatic Charts of the Oceans* shows that in over the northwest portion of the North c the average relative humidity is about 85 t. The *cP* air masses in process of transforma- *mP* are somewhat drier than average; hence the f 80 per cent was used as an average for the nder consideration. The potential temperature e specific humidity were assumed constant up lifting condensation level at the values de- termined by the surface pressure and temperature and a relative humidity of 80 per cent. Above that level the lapse rate was assumed to be saturation adiabatic with a relative humidity of 100 per cent. On these assumptions the lower part of the soundings over the sea was known.

To obtain soundings showing conditions in the same air over the land it was first necessary to determine where and when the air left the coast. In cases where there was little variation in trajectory with height, the column of air was considered to have moved as a unit; and the point and time at which the air left the coast, as determined from the surface trajectory, were representative for the air at all levels. The sounding at that point and time, obtained by interpolation among the known soundings, was used as the "initial sounding." In general, however, considerable variation of trajectory was observed, and a more complicated procedure was used. From the surface-pressure map and pressure differences obtained from the soundings, pressure charts were constructed for 1, 2, 3, and 4 kilometers. Upper winds from pilot-balloon observations were available as an additional check on the pressure patterns. A trajectory which terminated over the ship was constructed at each level. Thus, the point and time at which the air at each level left the coast were determined. The air between the surface and a height of 500 meters was assumed to move according to the surface trajectory, that between 500 and 1500 meters according to the 1000-meter trajectory, and so on. From the surface trajectory the time and place at which the air between the surface and 500 meters left the coast were determined, and the "initial sounding" for this interval of height was found by interpolation among the given soundings. Similar procedures gave sections of the sounding between other levels. The "initial sounding" used was a composite of these sections with the discontinuities smoothed. Composite soundings of both temperature and specific humidity were obtained.

When both ship and shore soundings had been constructed, the observed changes in sensible heat and water-vapor content could be calculated by comparing them.

Using average values of the sea-air differences in temperature and specific humidity, the total flux of sensible heat and the total evaporation were computed. Formulae were adapted from the theory of turbulent transfer for this purpose.

Since some of the water vapor that evaporates into the air condenses to form clouds, the observed change in water-vapor content could not be compared directly with the evaporation. Nor could the observed change in heat content be compared with the flux of sensible heat, since the observed change includes the latent heat liberated by the condensed vapor. Using the

following notations,

Q_{h_1} observed change in heat content
E_1 observed change in water-vapor content
Q_{h_2} total flux of sensible heat
E_2 total evaporation
C amount of condensed vapor
K ratio between observed changes and computed fluxes

the relationships can be written

$$E_1 = KE_2 - C,$$

$$Q_{h_1} = KQ_{h_2} + LC.$$

Multiplying the first by the latent heat and adding,

$$Q_{h_1} + LE_1 = K(Q_{h_2} + LE_2).$$

The values of the ratio K as determined in this manner serve as a check on the basic assumption. If, because of the great instability, the actual fluxes are much larger than the computed fluxes, the observed changes must also be larger than the computed fluxes and K must be significantly larger than unity. The values of K calculated from the data in the various weather situations deviated at random from unity, and the average was so close to unity that the validity of the basic assumption was established.

2. Theory for forecasting. As cP air moves out over warmer water, its content of heat and water vapor is increased by a flux of sensible heat and a flux of water vapor. As the process goes on, there is a continuous condensation of some of the water vapor to form clouds; a portion of the heat associated with evaporation is released as sensible heat and effects a change of the lapse rate at upper levels from dry to saturation adiabatic. In the theoretical treatment the two fluxes will be treated independently. This neglect of the interchange between them is justified, since the fluxes depend upon the gradients in the lowest 15 meters or so of the air and are independent of one another unless there is condensation in the lowest 15 meters (steam fog).

Theory of temperature changes. It is convenient to divide the air into three regions for purposes of discussion:

Let region 1 denote the very lowest layers of the air (see Figure 1), approximately 15 meters thick. As the cold air moves out over the warm water (first assumed to be of constant temperature), the thin film of air in direct contact with the sea surface immediately assumes the sea-surface temperature. Since the air at some distance from the sea surface is heated more slowly, a strongly superadiabatic lapse rate exists in region 1. There is a heat flux through the region associated with the vertical gradient of potential temperature.

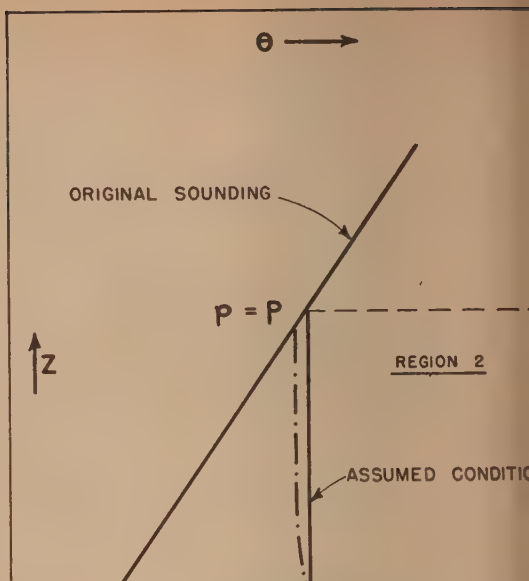


FIG. 1. Schematic representation of the changes in po temperature due to the flux of sensible heat alone in the formation of cP to mP air.

Region 2 is just above region 1 and is charact by a slightly superadiabatic lapse rate. This laps can be closely approximated with a dry adiabat d by the potential temperature at the top of reg The upper limit of region 2 is the level at whic adiabat intersects the original sounding. It w called the upper limit of temperature conve Region 3 will be defined in the following sectio

The heat flux through region 1 causes a conti increase in the potential temperature characteri region 2 and, it follows, in the height to which ten ture convection reaches. This increase goes on region 1 is characterized by a constant pot temperature, a condition to be expected only a great distances from the coast.

At any phase of the transformation, the po temperature of region 2 is determined by the pr and temperature at the top of region 1. The theo assume a constant pressure at the top of region forecast changes in the temperature. This tempe will be called the surface air temperature (T cumulations of heat in region 1 will be neglecte that region is only 15 meters thick.

Reference to Figure 1 will make the following ment plausible. The surface air temperature a phase will depend upon the initial surface air te ture (T_0), the integrated effect of the flux from t surface, and the mass of air over which th brought in by the flux is distributed. (Alt Figure 1 has potential temperature rather tha

e as coordinate, a change in surface air temper-
equivalent to a change in potential temperature
op of region 1 since the pressure is assumed to
stant.) The integrated flux depends on the
aneous flux (Q_h) and the distance over which it
n effective (X). The mass over which the heat
n distributed can be represented by the differ-
tween the surface pressure (p_s) and the pressure
top of region 2 (P) if a column of unit cross
is considered. Then the relationship can be

$$T = f(T_0, Q_h, X, p_s - P).$$

Q_h can be shown to depend on the surface air
ature and the average sea-surface temperature
nd $p_s - P$ is determined by the intersection of
inal and final soundings. The original sounding
acterized by T_0 and the initial average lapse
); the final sounding, by T and the adiabatic
te (Γ_a). With these substitutions the relation-
comes

$$T = F(T_0, X, \Gamma, \Gamma_a, \bar{T}_s).$$

$_s$ is a constant,

$$T = \psi(T_0, X, \Gamma, \bar{T}_s).$$

blem is to find the form of ψ.
e x-axis is placed along the trajectory of the
, the following expression describes the indi-
change in the heat content of a moving column
cross section:

$$\frac{d\Delta H}{dt} = \frac{\partial \Delta H}{\partial t} + u' \frac{\partial \Delta H}{\partial x},$$

ΔH is the difference between the instantaneous
original heat content. It is necessary to deal
is difference rather than with the heat content
nce the pressure at the top of region 2 decreases
ously during the transformation.
steady state,

$$\frac{d\Delta H}{dt} = u' \frac{d\Delta H}{dx}. \qquad (1)$$

cting horizontal mixing, the left-hand member
ion (1) represents the flux of sensible heat from
surface. If Q_h is the heat flux,

$$Q_h = - C_p \mu_e \frac{T'}{\theta'} \frac{d\theta'}{dz},$$

μ_e is the coefficient of eddy conductivity.
ing this coefficient with the eddy viscosity
),

$$\mu_e = \tau \Big/ \frac{du'}{dz}$$

or

$$Q_h = - C_p \tau \frac{T'}{\theta'} \frac{d\theta}{du'}.$$

In region 1, $T'/\theta' \doteq 1$; the stress can be assumed constant; and, since the region is thin enough for accumulations of heat to be negligible, the flux of heat is constant.

In this region, therefore,

$$Q_h \int_0^u du' = - C_p \tau \int_{T_s}^T dT',$$

where u and T are measured at the top of the region. Therefore,

$$Q_h u = C_p \tau (T_s - T).$$

According to Rossby and Montgomery (1), for moderate and strong winds,

$$\tau = \rho \gamma^2 u^2,$$

where, with u measured at about 15 meters, $\gamma^2 = 2.6 \times 10^{-3}$. Therefore,

$$\frac{d\Delta H}{dt} = Q_h = C_p \rho \gamma^2 u (T_s - T).$$

From the equation of state in the form $p/\rho = RT$ follows

$$\frac{d\Delta H}{dt} = \frac{C_p p_s \gamma^2 u}{R} \frac{T_s - T}{T}, \qquad (2)$$

where R is the gas constant for dry air and has a value of 287 kilojoules per ton per degree absolute.

The right-hand member of equation (1) represents the change in the heat content of the air mass as it moves in the x-direction. A consideration of the second law of thermodynamics leads to a usable expression for this quantity. Let h be heat content per unit mass. Then, for each particle of unit mass,

$$dh = C_v dT' + p d\alpha' = C_p dT' - \alpha' dp.$$

If the particle receives heat in an isobaric process, $dh = C_p dT'$. This assumption should be valid on the average, although in turbulent motion the individual particles do not move isobarically. Therefore,

$$h = C_p T'.$$

Defining H as the heat content of the column up to the upper limit of temperature convection, as given by the height Z where the pressure is P,

$$H = \int_0^Z \rho' h dz = C_p \int_0^Z \rho' T' dz = \frac{C_p}{g} \int_P^{p_s} T' dp.$$

At $x = 0$,

$$H_0 = \frac{C_p}{g} \int_P^{p_s} T_0' dp$$

and

$$\Delta H = \frac{C_p}{g} \int_P^{p_s} (T' - T_0') dp. \qquad (3)$$

At all values of x greater than zero, $T' = T - \Gamma_a\phi$, where Γ_a is the adiabatic lapse rate, ϕ the dynamic height, and T the surface air temperature.

Then,

$$\frac{T'}{T} = \left(\frac{p}{p_s}\right)^{R\Gamma_a}, \quad \text{where} \quad p \geq P. \tag{4}$$

Similarly,

$$\frac{T_0'}{T_0} = \left(\frac{p}{p_s}\right)^{R\Gamma}, \quad p \geq P, \tag{5}$$

where an average constant lapse rate has been introduced as an approximation to the original sounding.

At the pressure P, the final adiabat intersects the original sounding. It follows that $T_P' = T_{0P}'$, or from (4) and (5),

$$T\left(\frac{P}{p_s}\right)^{R\Gamma_a} = T_0\left(\frac{P}{p_s}\right)^{R\Gamma}. \tag{6}$$

Substituting (4) and (5) in (3),

$$\Delta H = \frac{C_p}{g}\int_P^{p_s}\left[T\left(\frac{p}{p_s}\right)^{R\Gamma_a} - T_0\left(\frac{p}{p_s}\right)^{R\Gamma}\right]dp.$$

Integrating,

$$\Delta H = \frac{C_p p_s}{g}\left\{\frac{T}{R\Gamma_a+1}\left[1-\left(\frac{P}{p_s}\right)^{R\Gamma_a+1}\right] - \frac{T_0}{R\Gamma+1}\left[1-\left(\frac{P}{p_s}\right)^{R\Gamma+1}\right]\right\},$$

and differentiating in respect to x,

$$\frac{d\Delta H}{dx} = \frac{C_p p_s}{g}\left\{\frac{1-\left(\frac{P}{p_s}\right)^{R\Gamma_a+1}}{R\Gamma_a+1}\frac{dT}{dx} - \left[\frac{T}{p_s}\left(\frac{P}{p_s}\right)^{R\Gamma_a} - \frac{T_0}{p_s}\left(\frac{P}{p_s}\right)^{R\Gamma}\right]\frac{dP}{dx}\right\}.$$

According to (6) the coefficient of dP/dx equals zero. Furthermore, using (6) and introducing

$$\frac{R\Gamma_a+1}{R(\Gamma-\Gamma_a)} = N-1,$$

one obtains

$$\frac{d\Delta H}{dx} = \frac{C_p p_s}{g(R\Gamma_a+1)}\left[1-\left(\frac{T}{T_0}\right)^{N-1}\right]\frac{dT}{dx}. \tag{7}$$

Substituting (2) and (7) into (1),

$$\frac{C_p p_s \gamma^2 u}{R}\frac{T_s - T}{T} = \frac{C_p p_s u'}{g(R\Gamma_a+1)}\left[1-\left(\frac{T}{T_0}\right)^{N-1}\right]\frac{dT}{dx}.$$

Defining a constant $M = [R/g\gamma^2(R\Gamma_a+1)] =$ meters per degree,

$$udx = Mu'\left[\frac{T}{T_s - T} - \frac{T^N}{T_0^{N-1}(T_s - T)}\right]dT$$

Finally it is assumed that the ratio u/u' is cons This assumption is never strictly fulfilled, but, i cP air mass is sufficiently homogeneous in the zontal at all levels, variations of trajectory with h will not affect the heat content of the final soun If the air is not homogeneous, variations in traje are accounted for by constructing a composite "i sounding." According to a recent study at Sc Institution of Oceanography, $u/u' = 0.7$ for s adiabatic lapse rates, where u' is interpreted a geostrophic wind speed.

Then

$$0.7dx = M\left[\frac{T}{T_s - T} - \frac{T^N}{T_0^{N-1}(T_s - T)}\right]dT$$

Assume a constant sea-surface temperature $\bar{T}_s$ a $v = T/\bar{T}_s$. Then

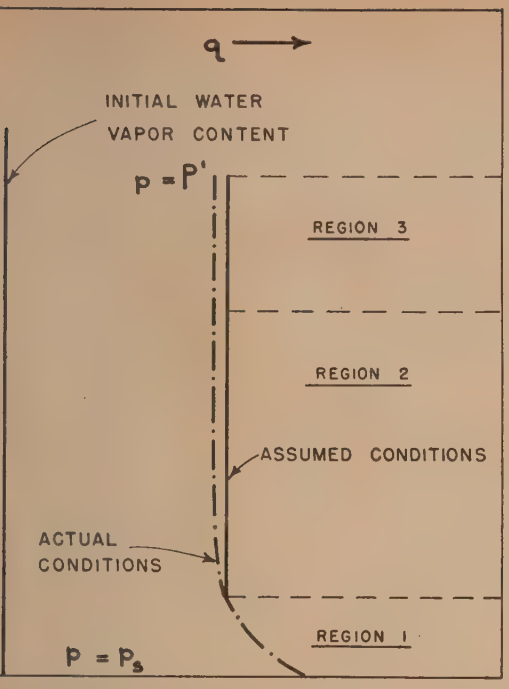
$$\int_0^X \frac{0.7dx}{M\bar{T}_s} = \int_{T_0/\bar{T}_s}^{T/\bar{T}_s}\left[\frac{v^N}{v_0^{N-1}(v-1)} - \frac{v}{v-1}\right]dv;$$

$$\frac{0.7X}{M\bar{T}_s} = \frac{1}{v_0^{N-1}}\int_{T_0/\bar{T}_s}^{T/\bar{T}_s}\frac{v^N}{v-1}dv - \frac{T}{\bar{T}_s} + \frac{T_0}{\bar{T}_s} - \ln\frac{T/\bar{T}_s - 1}{T_0/\bar{T}_s - 1}$$

The integral on the right-hand side of (8) can taken generally but was evaluated for certain of the function N. Plates I to VI represent tion (8) for various values of the initial lapse that is, they represent graphically the general fu $T = \psi(T_0, \Gamma, X, \bar{T}_s)$. The limits of the graphs been liberally selected and should cover every p case. A description of their use is included applications.

Theory of specific humidity changes. As the dr air moves out over the water, the vapor pressure film of air in direct contact with the sea surface re always equal to the vapor pressure at the sea s There is a flux of water vapor through region 1 ated with the strong gradient of specific hu which occurs in that region. If condensation is ig there will be a slight gradient of specific humi region 2. Since, however, there is large-scale mi region 2, the specific humidity in that region is constant with height.

The condensation of water vapor that a occurs brings about a saturation adiabatic lap somewhere in region 2, so that water vapor a heat set free by condensation will be transpo greater heights than the top of region 2. Re



Schematic representation of the changes in water-vapor uring the transformation cP to mP air, if it is assumed of the vapor condenses.

the portion of the atmosphere between region 2 upper limit of diffusion of water vapor, i.e., the which the final saturation adiabat intersects nal sounding. In region 3 as well as in the upper region 2, the sum of the water vapor and the ed water must be approximately equal to cific humidity at the base of region 2 (see 2 and 3).

evelopment of the theory for changes in water- ontent parallels that for changes in heat con- condensation is neglected and the x-axis is ne particle trajectory, the expression for the ıal change in the vapor content of a column can en

$$\frac{dW}{dt} = \frac{\partial W}{\partial t} + u' \frac{\partial W}{\partial x},$$

V is the water-vapor content of the column. steady state,

$$\frac{dW}{dt} = u' \frac{\partial W}{\partial x}. \qquad (9)$$

eft-hand member of equation (9) represents poration from the sea surface. If E is the tion,

$$E = -\mu_e \frac{dq}{dz},$$

$_e$ is the eddy coefficient of diffusivity of water vapor and q is specific humidity. If this coefficient is identified with the coefficient of eddy viscosity, a treatment similar to that for the flux of sensible heat yields

$$\frac{dW}{dt} = E = \rho\gamma^2 u(q_s - q). \qquad (10)$$

The right-hand member of (9) represents the change in the water-vapor content of the air mass as it moves in the x-direction. If the specific humidity up to the top of region 3 is assumed constant with height,

$$W = q \int_0^{z'} \rho dz = \frac{q}{g}(p_s - P')$$

or

$$u' \frac{dW}{dx} = \frac{u'}{g} \frac{d}{dx} [q(p_s - P')]. \qquad (11)$$

Substituting (10) and (11) in (9),

$$\frac{u'}{g} \frac{d}{dx} [q(p_s - P')] = \rho\gamma^2 u(q_s - q).$$

Assuming $0.7u' = u$, as in the theory of temperature changes,

$$(p_s - P')dq - qdP' = 0.7\rho\gamma^2 g(q_s - q)dx. \qquad (12)$$

Equation (12) contains three variables, q, P' and x, and in order to solve the problem another relation between these must be established. Since x is a function of the temperature change and since temperature and specific humidity, in conjunction with the original sounding, determine the pressure P', another relation can be found; but when it is introduced into (12), the resulting equation cannot be integrated.

If q can be introduced as a simple, approximate function of x on the right side of (12), the equation can be integrated and a closer approximation to q in any given situation can be made. An empirical study might yield a functional relationship that is close enough to permit fairly accurate forecasts.

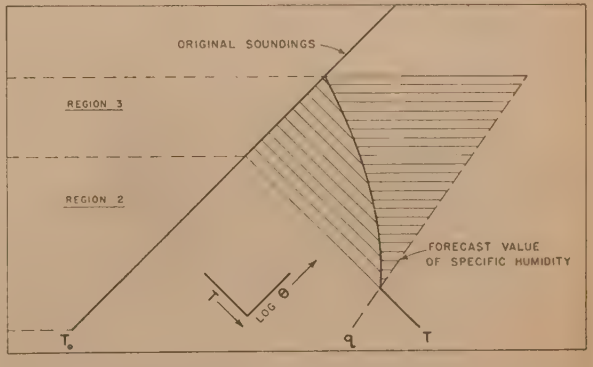


FIG. 3. Representation of the final forecast on the tephigram. The hatched areas show the interchange between latent and sensible heat brought about by the condensation of water vapor.

3. Applications to forecasting.

Description of plates. Plates I to VI are used for quantitative forecasts of the changes in temperature during the transformation *cP* to *mP*. The variables that determine the increase in the heat content of an air column are the initial lapse rate in the column (Γ), the initial temperature at the base of the column (T_0), the distance which the column moves over the water (X), and the average sea surface temperature over the column trajectory ($\bar{T}_s$).

Each plate is drawn for a different value of the initial lapse rate. The shift of the curves from plate to plate is approximately linear. In certain regions of the plates the temperatures as obtained from adjacent plates differ by as much as six degrees, so that interpolation will often be necessary for initial lapse rates that lie between the values for which plates have been made. Linear interpolation will give sufficient accuracy.

The initial surface air temperature is included in the ratio $T_0/\bar{T}_s$. The curves on the plates represent equal values of this ratio. Because of the scarcity of information on Siberian air masses, the curves cover a wide range of this parameter.

The distance which the column moves over water is included in the ratio $X/\bar{T}_s$, the horizontal coordinate. The plates cover a range from two kilometers to seven thousand kilometers, approximately. In the Pacific, trajectories in excess of the latter value can occur. It should be noted that the value of the final surface air temperature given by the plates will represent a lower limit rather than the expected temperature at these great distances since, for the lengths of time involved, radiation will not be negligible.

The average sea-surface temperature is included in all ratios on the plates.

The intersection of the vertical corresponding to a given value of $X/\bar{T}_s$ with a given member of the $T_0/\bar{T}_s$ family determines a value of $T/\bar{T}_s$ from which the final value of the surface air temperature can be found.

Procedure in forecasting. 1. The trajectory of the air column is forecast. Two types of situations may be encountered.

a. With knowledge of the sounding at a given point on the coast it may be desirable to determine the temperature of the same air at any point over the water at some later time.

b. In order to determine the temperature at a given time for some point over the ocean, it may be necessary to determine where and when the air which has arrived at the point left the coast.

When the trajectory varies only slightly with height or when the air mass over land is quite homogeneous in the horizontal and the origin is from over land at all levels, the trajectory can be established from the surface map and surface prognostic charts. The "i sounding" is the sounding at the point and tir which the air left the coast according to the su trajectory. If the above conditions are not ful trajectories must be forecast at upper levels a *composite* "initial sounding" must be construct explained in the introduction.

It should be noted that the temperature chang lower levels must be considered in forecasting an air trajectory. Prognostic pressure charts at the su and at an upper level involve a forecast of the temperature between the levels. This means tha first step is a qualitative forecast of the temper changes in order to establish the composite "i sounding," and the next step is to compute the cha The computation, therefore, represents a secon proximation. In some cases it may be desirable to a third approximation by constructing a new traje which is based on computed temperature soun and carrying out new computations. In general, would be gained from such refinements becaus results are not much altered by a moderate cha the trajectories.

2. An average sea-surface temperature ove trajectory is determined. Isotherms from mean mo charts should give sufficient accuracy, since an er the computation of heat flux will usually lead t a small error in the temperature. In general, the value of the sea-surface temperature shou weighted more heavily than the initial valu practical methods for determining the averages be based upon experience in the application method. From a qualitative examination of the pl process, it can be concluded that the compa weight given to the final value should be grea large distances from the coast or light wind vel than for short distances or strong wind velocit the discussion of forecasts given on page 102 ar cated tentative rules for obtaining the averages

3. The ratios $X/\bar{T}_s$ and $T_0/\bar{T}_s$ are formed. kilometers and is measured along the *surface* traje All temperatures are on the absolute scale. T_0 from the shore sounding.

4. An average value of the lapse rate up to a trary pressure, say 700 mb, is determined fro "initial sounding."

5. The average initial lapse rate determines plate or plates are to be used in making the fo When the initial lapse rate does not coincide wi of the values for which the plates are drawn, the between which the lapse rate falls are used.

6. On each plate $X/\bar{T}_s$ defines a vertical. The section of the vertical with the curve correspon the computed value of $T_0/\bar{T}_s$ gives a value of When readings have been made from two plat final value of $T/\bar{T}_s$ is found by linear interpola

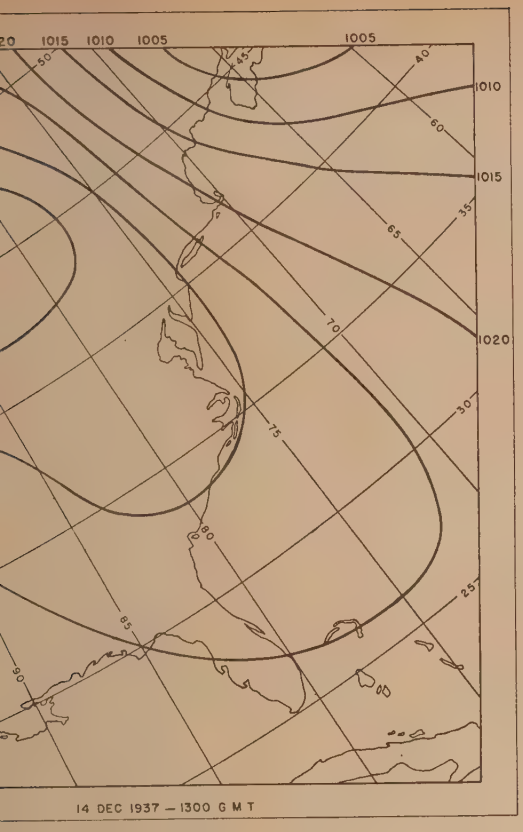


FIGURE 4.

rom $T/\bar{T}_s$ the temperature T is calculated.
dry adiabat drawn through T determines a
f intersection with the original sounding. If the
re at this level is near 700 mb or any other
re assumed in step 4, this value of T will be the
recast. If, however, the pressure at the level of
ction differs from the pressure assumed in 4 in
way as to make the lapse rate from step 4 not
entative of the sounding up to the new level, the
of T will constitute only an approximation to the
rature. In these cases, a new average lapse rate
n and a closer approximation to the temperature
le. It is unlikely that a third approximation will
e necessary.

eatures such as a strong inversion make it im-
le to characterize the sounding adequately by a
linear lapse rate, the forecast can be carried out
steps. First, using the lapse rate in the inversion
the initial temperature at the base, the tempera-
necessary to wipe out the inversion, and an
ge sea-surface temperature close to the coast; the
ce necessary to wipe out the inversion can be
ed from the plates. Second, using the lapse rate
mperature from the new sounding and a distance
to the original distance minus the correction
the first step), the forecast can be made.

4. The specific humidity forecast. With the present theory quantitative forecasts of changes in specific humidity cannot be made from the physical variables in each situation, but the specific humidity can be approximately forecast by assuming a value for the relative humidity. A value of 80 per cent gave good results in the empirical study and is suggested for use in forecasting. From the relative humidity and the temperature the specific humidity can be determined and the final sounding constructed.

The final sounding gives information on the clouds and turbulence, as well as some information on the precipitation, which characterize the final condition in the air mass. In interpreting the sounding the following facts should be borne in mind:

1. A slight error in specific humidity will give a comparatively large error in the estimation of the height of the cloud base.

2. A slight error in specific humidity will give a large error in the height of the cloud top only when the sounding is unstable aloft. This condition is seldom encountered in *cP* air.

5. Example. Figures 4 and 5 show the flow patterns over the eastern part of the United States and off the coast on December 14 and 15, 1937. These figures are taken from the *Daily Synoptic Series—Historical*

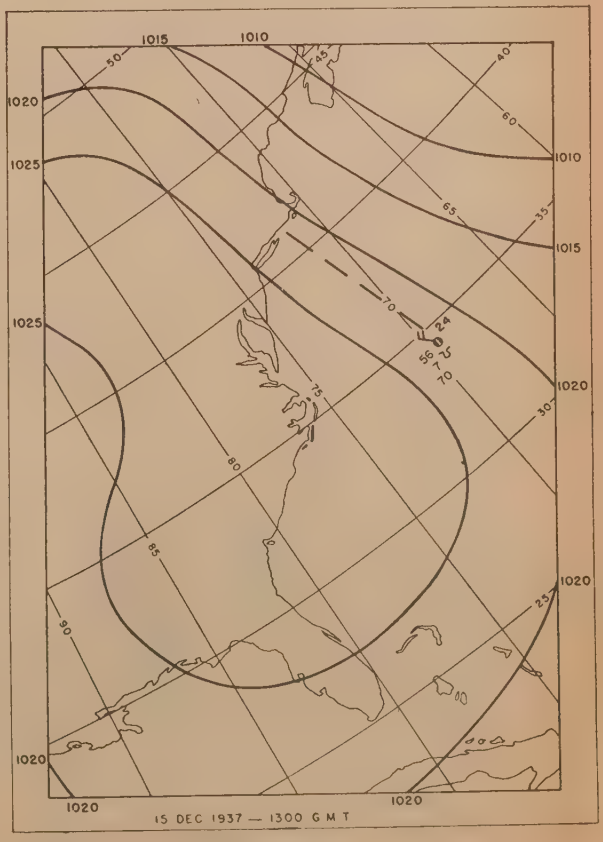


FIGURE 5.

Weather Maps—Northern Hemisphere Sea Level. In Figure 5 the approximate trajectory of the air which is over the ship near 70°W 35°N at 1300 GMT on the fifteenth is shown. The air left the coast near Block Island at about 1900 on the fourteenth. The sounding at this point and time was determined by interpolation between the Boston and Lakehurst soundings for the fourteenth and fifteenth. Figure 6 contains a plot of the interpolated sounding on a tephigram.

To facilitate reference to the description of forecasting procedure, each step in the example will be given the same number as the description of that step on pages 100 and 101.

1. The length of the trajectory is measured from Figure 5 at about 780 km.

2. The average sea-surface temperature for the month of December in the vicinity of Block Island is 281.5°. At the ship it is 294°. An examination c cases indicates that for distances greater than 60 the final value of the sea-surface temperature shou taken as the average. Thus, the average sea-su temperature $\bar{T}_s$ is 294°.

3. The temperature at the base of the s sounding (Fig. 6) is 265°. Therefore $X/\bar{T}_s = 2.7$ $T_0/\bar{T}_s = 0.902$.

4. The average lapse rate up to 700 m − 0.17°/100 m.

5. Since the lapse rate is between 0 and − 0.25° m, Plates IV and V are used.

6. From Plate IV, $T/\bar{T}_s = 0.971$.
From Plate V, $T/\bar{T}_s = 0.977$.
The interpolated value is 0.975.

7. The first approximation to the temperature 286.5°. The adiabat through 286.5° and the su

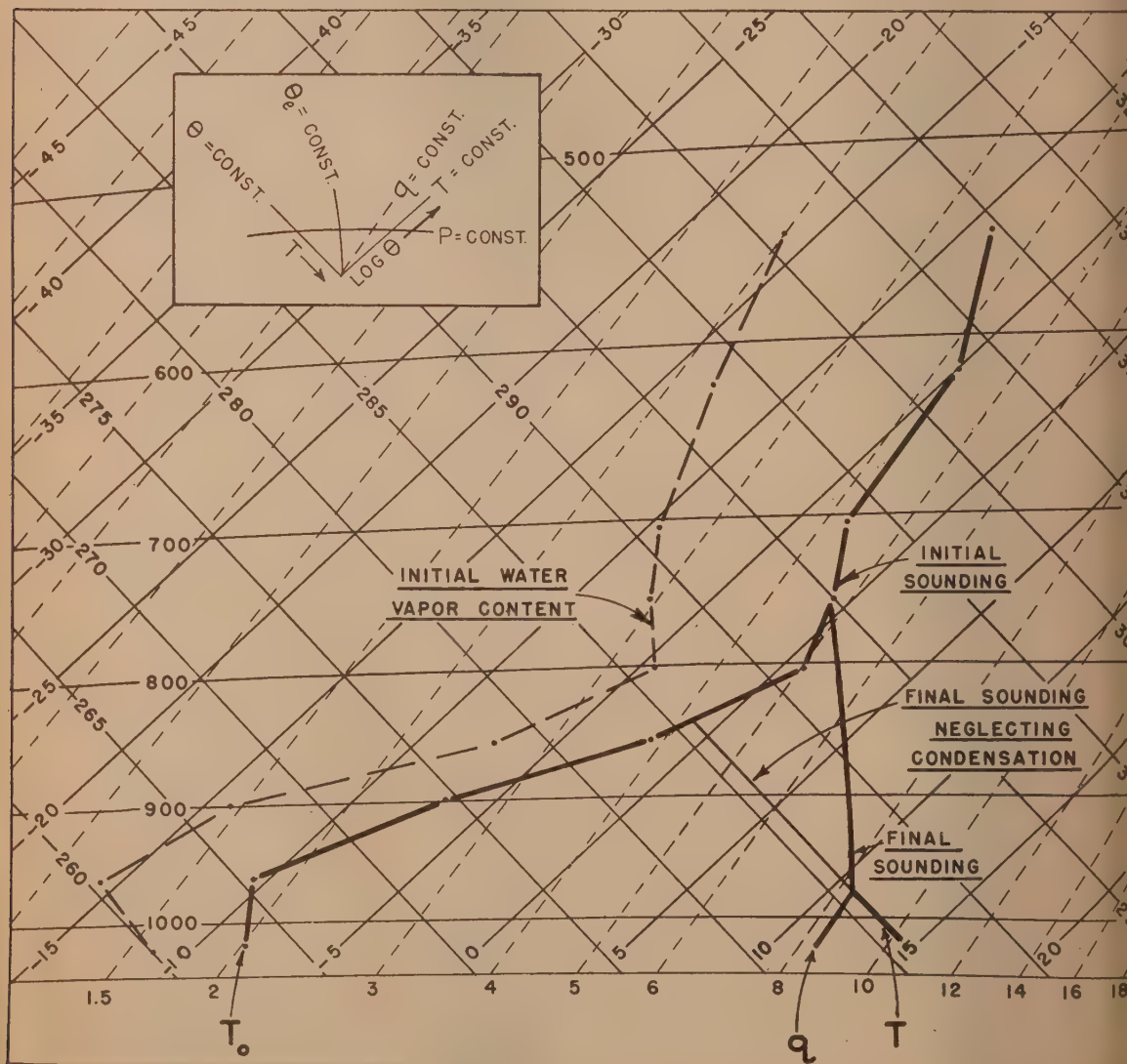


FIG. 6. Graphical representation on a tephigram of a sample forecast.

TABLE 1

Sample Forecasts Using $\bar{T}_s = (T_{s_i} + 3T_{s_f})/4$

gth er- er tory n	Initial surface air temp. °A	Initial sea-surface temp. °A	Final sea-surface temp. °A	Average sea-surface temp. °A	Average lapse rate °A/100 m	$\frac{X}{\bar{T}_s}$	$\frac{T_0}{\bar{T}_s}$	$\frac{T}{\bar{T}_s}$	Forecast final temp. °A	Observed final temp. °A	Temperature change		Error °A
											Forecast °A	Observed °A	
55	274.5	281.5	283.0	282.5	0.47	1.2	0.972	0.990	279.5	277.5	5.0	3.0	2.0
70	265.0	281.5	289.5	287.5	0.00	1.3	0.922	0.968	278.0	279.0	13.0	14.0	−1.0
20	267.5	277.0	284.0	282.0	0.36	1.5	0.948	0.980	276.0	276.0	8.5	8.5	0.0
30	268.5	277.0	284.0	282.0	0.31	1.5	0.953	0.984	277.5	276.0	9.0	7.5	1.5
40	271.0	284.0	287.0	286.0	0.29	1.5	0.949	0.982	280.5	278.5	9.5	7.5	2.0
90	267.5	282.5	292.5	290.0	0.27	1.7	0.923	0.968	280.0	279.0	12.5	11.5	1.0
90	266.5	282.0	285.0	284.0	0.13	1.8	0.938	0.979	277.5	277.0	11.0	10.5	0.5
90	264.0	282.0	291.0	289.0	0.25	1.7	0.913	0.963	278.0	278.0	14.0	14.0	0.0
20	263.5	277.5	284.0	282.5	0.28	1.8	0.933	0.976	275.5	275.5	12.0	12.0	0.0
50	263.5	277.5	284.5	282.5	0.30	1.9	0.932	0.977	276.0	275.0	12.5	11.5	1.0
55	262.0	278.5	291.0	288.0	0.14	1.9	0.910	0.967	278.5	281.0	16.5	19.0	−2.5
55	264.0	277.5	285.5	283.5	0.06	2.0	0.932	0.979	277.0	277.5	13.0	13.5	−0.5
50	274.0	281.0	282.0	282.0	0.50	2.0	0.972	0.994	280.0	281.0	6.0	7.0	−1.0
50	265.0	282.0	293.0	290.0	−0.18	1.9	0.917	0.975	283.0	283.0	18.0	18.0	0.0
90	271.0	283.0	291.0	289.0	0.26	2.0	0.938	0.980	283.0	283.0	12.0	12.0	0.0
20	266.0	281.0	292.0	289.0	−0.05	2.1	0.920	0.977	282.5	282.0	16.5	16.0	0.5
30	266.0	283.0	287.5	286.5	0.10	2.2	0.929	0.978	280.5	280.5	14.5	14.5	0.0
30	270.0	281.0	292.5	289.5	0.36	2.3	0.933	0.978	283.0	285.0	13.0	15.0	−2.0
30	265.0	281.5	294.0	291.0	−0.42	2.7	0.911	0.983	286.5	286.0	21.5	21.0	0.5
30	267.5	279.0	293.0	289.5	0.33	2.7	0.924	0.978	283.0	286.0	15.5	18.5	−3.0
30	265.5	279.0	291.0	288.0	0.12	2.7	0.922	0.979	282.0	283.0	16.5	17.5	−1.0
90	263.5	277.5	289.0	286.0	0.23	2.8	0.922	0.977	279.5	281.0	16.0	17.5	−1.5
90	264.0	277.5	289.0	286.0	0.09	2.8	0.923	0.980	280.0	281.0	16.0	17.0	−1.0
90	270.5	278.5	292.5	287.0	0.40	3.1	0.943	0.984	282.5	284.0	12.0	13.5	−1.5
50	267.0	282.0	293.0	290.0	−0.10	3.3	0.921	0.986	286.0	288.0	19.0	21.0	−2.0
10	265.5	281.5	295.0	291.5	−0.18	3.8	0.911	0.985	287.0	289.5	21.5	24.0	−2.5
20	264.0	281.0	293.0	290.0	−0.29	4.2	0.911	0.988	286.5	288.0	22.5	24.0	−1.5
40	272.0	282.0	294.5	291.5	0.32	4.3	0.933	0.988	288.0	288.5	16.0	16.5	−0.5

of 1022 mb intersects the original sounding at (see Fig. 6).

he average lapse rate up to 850 mb is /100 m.

ates V and VI are used.

ne new interpolated value of $T/\bar{T}_s$ is 0.979.

ne second approximation to the temperature is The adiabat through 287.5° intersects the sounding at 845 mb and no further approxima- ecessary.

emperature reported by the ship is 286°, so forecast is 1½ degree in error.

aturation specific humidity at 287.5° is 10.5 hen 80 per cent relative humidity corresponds to 8.4 g/kg. These values determine the condensation level and the saturation adiabat which intersects the original sounding at the upper limit of region 3. The final sounding in the example is shown in Figure 6.

6. Results of forecasts. Table 1 gives the results of 28 forecasts based on an average sea-surface temperature in which the final value has been weighted three times as heavily as the initial. Since temperatures are measured to the nearest degree Fahrenheit, forecasts were attempted to the nearest half-degree Centigrade. The forecasts for distances below 650 km check rather closely, the maximum error being 2.5°C, but for distances greater than 650 km the forecast values are too low with only one exception. This can be attributed

TABLE 2

Sample Forecasts Using $\bar{T}_s = T_{s_f}$

Length of over-water trajectory km	Initial surface air temp. °A	Final sea-surface temp. °A	Average lapse rate °A/100 m	$\frac{X}{\bar{T}_s}$	$\frac{T_0}{\bar{T}_s}$	$\frac{T}{\bar{T}_s}$	Forecast final temp. °A	Observed final temp. °A	Temperature change		Error °A
									Forecast °A	Observed °A	
680	270.0	292.5	0.36	2.3	0.923	0.973	284.5	285.0	14.5	15.0	−0.5
780	265.0	294.0	−0.42	2.7	0.901	0.978	287.5	286.0	22.5	21.0	1.5
780	267.5	293.0	0.33	2.7	0.913	0.970	284.0	286.0	16.5	18.5	−2.0
780	265.5	291.0	0.12	2.7	0.914	0.975	283.5	283.0	18.0	17.5	0.5
800	263.5	289.0	0.23	2.8	0.911	0.972	281.0	281.0	17.5	17.5	0.0
800	264.0	289.0	0.09	2.8	0.914	0.974	281.5	281.0	17.5	17.0	0.5
900	270.5	292.5	0.40	3.1	0.925	0.977	286.0	284.0	15.5	13.5	2.0
960	267.0	293.0	−0.10	3.3	0.911	0.983	288.0	288.0	21.0	21.0	0.0
1110	265.5	295.0	−0.18	3.8	0.900	0.979	288.5	289.5	23.0	24.0	−1.0
1220	264.0	293.0	−0.29	4.2	0.901	0.988	289.5	288.0	25.5	24.0	1.5
1240	272.0	294.5	0.32	4.2	0.924	0.984	289.5	288.5	17.5	16.5	1.0

TABLE 3

Forecasts from MIT Data

Case No.	Length of over-water trajectory km	Initial surface air temp. °A	Average sea-surface temp. °A	Average lapse rate 0–5000 ft °A/100 m	$\frac{X}{\overline{T}_s}$	$\frac{T_0}{\overline{T}_s}$	$\frac{T}{\overline{T}_s}$	Forecast final temp. °A	Observed final temp. °A	Temperature change	
										Forecast °A	Observed °A
1	925	257	278	0.20	3.3	0.925	0.983	273	274	16	17
2	1480	248	279	0.40	5.3	0.889	0.972	271	271	23	23
3	1850	256	278	0.47	6.7	0.921	0.986	274	273	18	17
4	1020	268	279	0.80	3.7	0.960	0.990	276	272	8	4
5	1850	258	278	0.20	6.7	0.929	0.993	276	274	18	16
6	1020	271	277	0.60	3.7	0.979	0.999	277	277	6	6
7	1020	253	277	0.13	3.7	0.914	0.981	272	271	19	18
8	925	249	276	−0.27	3.3	0.902	0.985	272	272	23	23
9	1290	253	276	0.53	4.7	0.916	0.980	271	272	18	19
10	1290	253	275	0.33	4.7	0.920	0.984	271	273	18	20
11	1020	251	277	0.00	3.7	0.906	0.980	272	273	21	22
12	790	261	275	0.27	2.9	0.949	0.990	272	273	11	12
13	1250	262	278	0.13	4.5	0.942	0.994	276	276	14	14
14	650	261	278	−0.13	2.3	0.939	0.987	274	273	13	12
15	740	259	276	0.27	2.7	0.939	0.985	272	271	13	12
16	1290	253	277	0.53	4.7	0.915	0.977	271	273	18	20
17	800	267	276	0.25	2.9	0.966	0.996	275	275	8	8
18	925	270	275	0.53	3.4	0.981	0.999	275	275	5	5
19	925	257	275	−0.27	3.4	0.934	0.994	273	275	16	18
20	925	263	275	0.13	3.4	0.956	0.995	274	274	11	11
21	1110	265	276	0.20	4.0	0.960	0.996	275	276	10	11
22	925	253	276	0.40	3.4	0.917	0.974	269	266	16	13
23	925	269	278	0.60	3.3	0.968	0.995	267	276	18	17
24	740	270	276	0.40	2.7	0.978	0.998	275	275	15	15
25	740	269	277	0.33	2.7	0.971	0.997	276	276	17	17
26	1110	250	277	0.07	4.0	0.903	0.980	271	270	21	20
27	870	262	276	0.73	3.2	0.950	0.981	271	269	9	7
28	925	258	278	0.40	3.3	0.928	0.980	272	274	14	16
29	1020	270	275	0.07	3.7	0.982	1.000	275	277	5	7
30	830	261	276	0.60	3.0	0.946	0.982	271	269	10	8
31	2590	246	278	−0.13	9.3	0.885	0.993	276	274	30	28
32	2040	252	276	0.33	7.4	0.913	0.997	275	275	23	23
33	830	273	278	0.33	3.0	0.982	1.000	278	277	5	4
34	1570	263	278	0.07	5.7	0.946	0.996	277	277	14	14
35	1020	265	278	0.40	3.7	0.954	0.992	276	273	11	8
36	1290	266	278	0.26	4.6	0.957	0.997	277	275	11	9
37	830	273	278	0.33	3.0	0.983	0.999	278	277	5	4
38	740	273	278	0.33	2.7	0.983	0.999	278	276	5	3
39	830	276	278	0.47	3.0	0.992	1.000	278	277	2	1
40	1110	275	278	0.53	4.0	0.989	1.000	278	277	3	2
41	830	271	278	0.20	3.0	0.975	0.999	278	276	7	5
42	1290	266	278	0.47	4.6	0.957	0.993	276	277	10	11
43	1290	265	278	0.07	4.6	0.954	0.997	277	275	12	10
44	1850	263	279	0.47	6.6	0.942	0.993	277	276	14	13
45	1200	273	291	0.47	4.1	0.938	0.985	287	285	14	12
46	1110	271	290	0.67	3.8	0.935	0.977	283	282	12	11
47	425	273	277	0.13	1.5	0.985	0.998	276	274	3	1
48	1160	263	276	0.13	4.2	0.954	0.996	275	273	12	10
49	2020	272	291	0.47	6.9	0.935	0.992	289	289	17	17
50	330	260	274	0.47	1.2	0.949	0.977	268	268	8	8
51	1335	281	289	0.40	4.6	0.930	0.987	285	286	4	5
52	1120	264	288	0.20	3.9	0.916	0.982	283	281	9	7
53	1535	274	289	0.73	5.3	0.948	0.993	287	289	13	15
54	1175	263	289	0.67	4.1	0.910	0.973	281	281	8	8
55	965	252	289	0.07	3.3	0.872	0.962	278	281	26	29
56	1090	272	289	0.07	3.8	0.941	0.993	287	287	15	15
57	1505	257	291	−0.20	5.2	0.883	0.984	286	284	29	27
58	1640	260	291	0.20	5.6	0.894	0.982	286	287	26	27
59	830	262	290	0.27	2.9	0.904	0.970	281	286	19	24
60	240	269	275	0.73	0.85	0.979	0.993	273	273	4	4
61	680	266	285	0.53	2.4	0.934	0.976	278	276	12	10
62	830	262	286	0.20	2.9	0.916	0.977	279	280	17	18
63	1640	268	284	0.53	5.8	0.944	0.992	282	278	14	10
64	505	268	274	0.53	1.8	0.978	0.995	273	272	5	4
65	820	268	290	0.50	2.8	0.925	0.979	284	285	16	17
66	320	274	277	0.53	1.2	0.993	1.000	277	277	3	3
67	1530	274	292	0.33	5.2	0.939	0.991	289	288	15	14
68	400	274	279	0.40	1.4	0.982	0.997	278	278	4	4

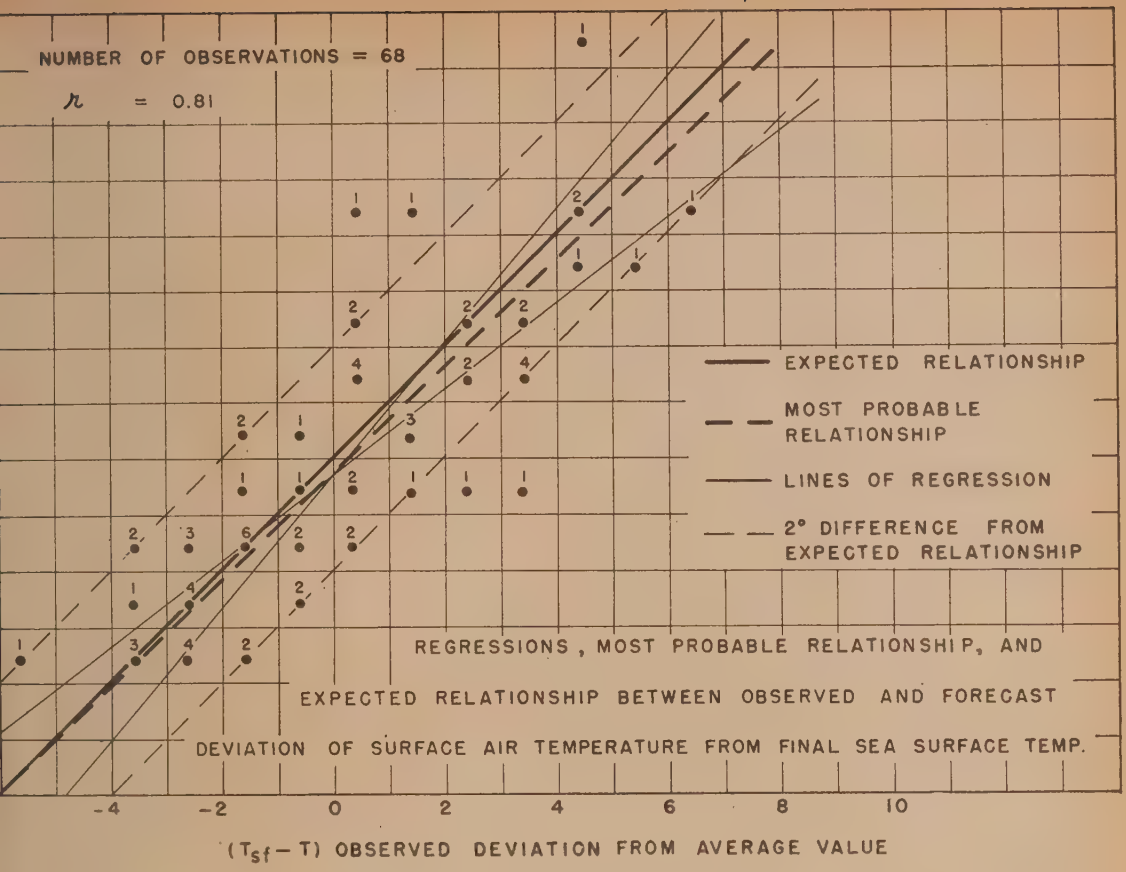


FIGURE 7.

causes: (a) Radiation may not be negligible for reater distances. (b) The air has had more time e to equilibrium with the final value of the sea- temperature, so that too much weight has been o the original value.

ng the average sea-surface temperature equal inal value, the forecasts were repeated with the which are summarized in Table 2. These new ts check closely, indicating that it is correct to e final surface temperature greater weight when jectory over water is long.

e 3 presents the results of the application forecasting method to data which were made le through the courtesy of the officers at AF Weather Station, Massachusetts Institute nology. In making these forecasts, the rules $T_{s_i} + 3T_{s_f})/4$ for $X < 650$ km and $\bar{T}_s = T_{s_f}$ > 650 km were applied without further modi- . Here T_{s_i} is the initial sea-surface temperature is the final sea-surface temperature. Radiosonde ge is rather sparse in the regions of these data, the "initial soundings" are subject to some racies. Because of this, the lapse rates used are cases the differences between the temperatures at sea level and 5000 ft, as obtained from isotherms on the constant level charts. In Table 4 the results of the 68 forecasts on the MIT data are summarized. The correlation coefficients in this table show that the size of the error is quite independent of the distance from shore and the magnitude of the temperature change. The only coefficient which has any validity is that between the error and the observed temperature change. It reveals a slight tendency toward underesti- mating large changes and overestimating small ones. In Figure 7, the observed deviation of the final sea-air temperature difference from the average value is plotted against the forecast deviation. The points corresponding to individual forecasts are entered. The

TABLE 4.

Number of cases	68
Mean absolute error	1.3°
Average of all errors	0.4°
% within ± 1°	62
% within ± 2°	91
% within ± 3°	96
% within ± 4°	99
% within ± 5°	100
Correlation coefficients	r
Error and distance	0.06
Absolute error and distance	0.20
Error and observed temperature change	−0.41
Absolute error and observed temperature change	0.12

light solid lines are the two curves of regression. The coefficient of correlation between observed and forecast deviation is 0.81. Forecasts of the average sea-air temperature difference would give the horizontal line corresponding to zero forecast deviation. Perfect forecasts would give the heavy solid line. The most probable linear relationship (see (2)) between the observed and forecast deviations, computed from the curves of regression, is shown by the heavy dashed line. It differs very little from the line representing perfect forecasts which indicates that the errors are random. The light dashed lines correspond to errors of ± 2 degrees, within which 91 per cent of the forecasts fall.

Figure 7 shows that the method provides considerably better forecasts than could be obtained by using the constant average difference between air and water and the sea-surface temperature.

The accuracy obtained in these forecasts will not be obtained in actual practice since the trajectory ca be forecast as accurately as it has been constructe these cases. The temperature changes, however, not very sensitive to slight variations in trajecto

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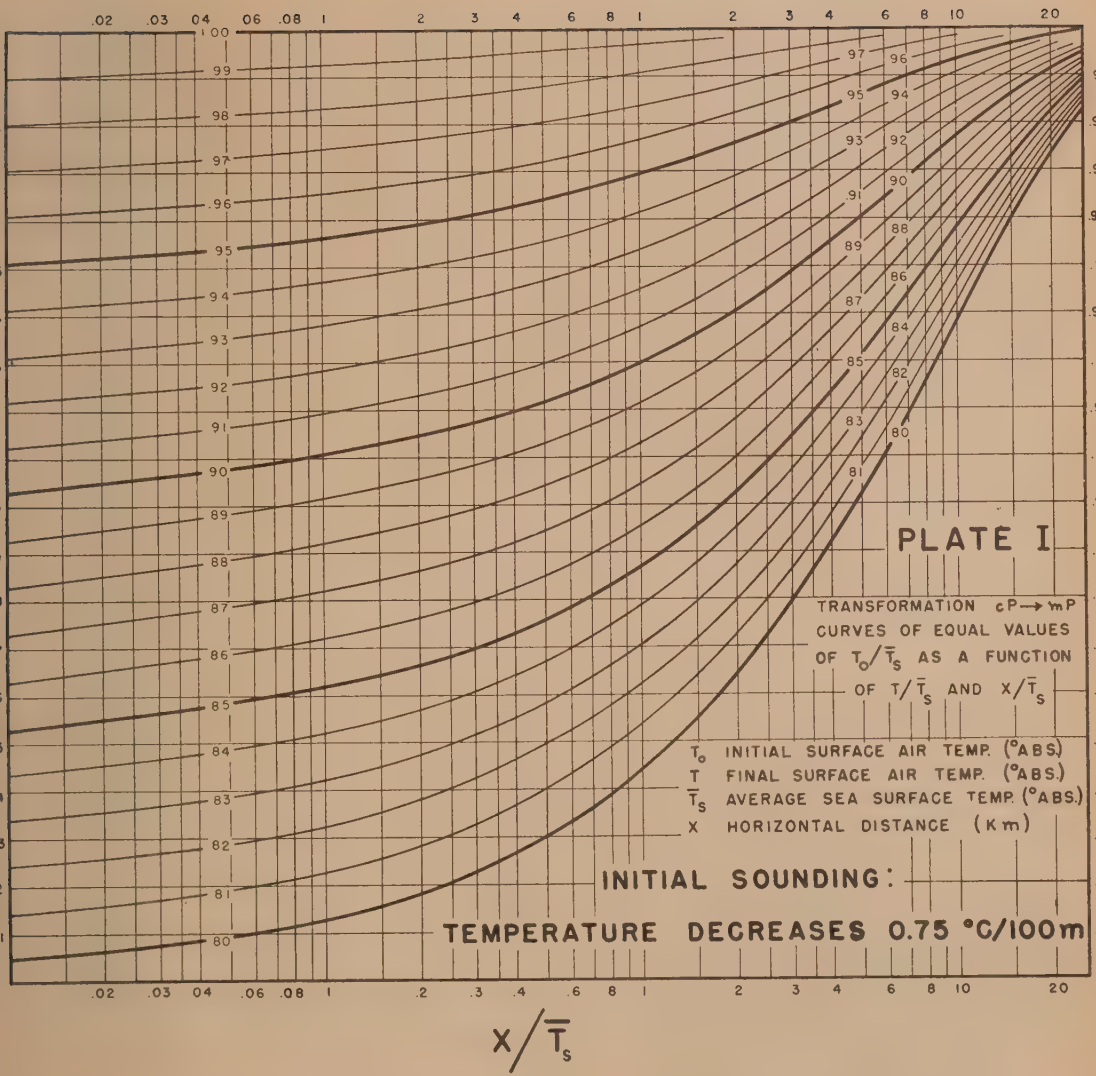
PLATE I
TRANSFORMATION cP → mP
CURVES OF EQUAL VALUES
OF $T_o/\bar{T}_s$ AS A FUNCTION
OF $T/\bar{T}_s$ AND $X/\bar{T}_s$
T_o INITIAL SURFACE AIR TEMP. (°ABS.)
T FINAL SURFACE AIR TEMP. (°ABS.)
$\bar{T}_s$ AVERAGE SEA SURFACE TEMP. (°ABS.)
X HORIZONTAL DISTANCE (Km)
INITIAL SOUNDING:
TEMPERATURE DECREASES 0.75 °C/100m
$X/\bar{T}_s$

PLATE I.

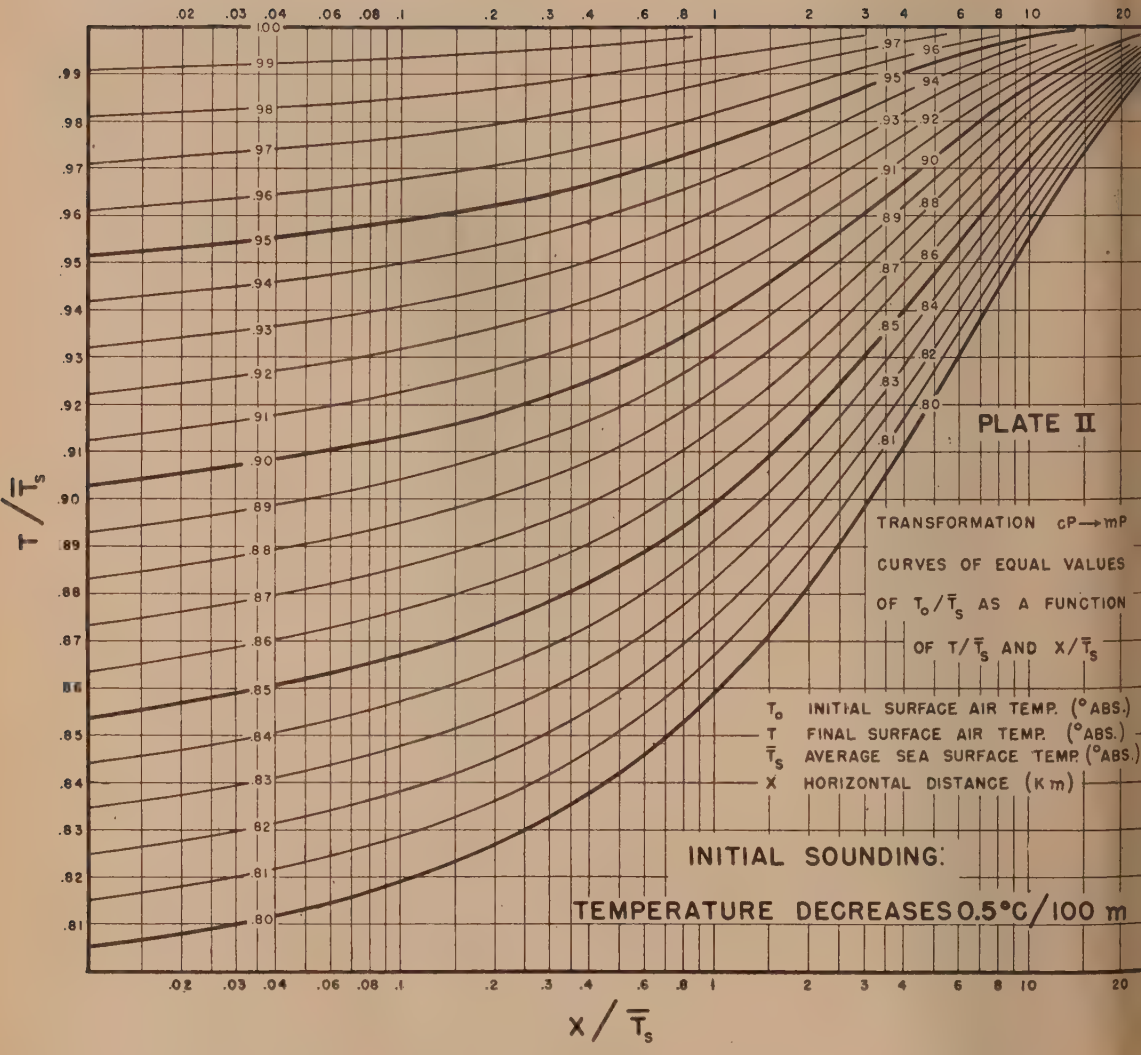
PLATE II
TRANSFORMATION cP → mP
CURVES OF EQUAL VALUES
OF $T_o/\bar{T}_s$ AS A FUNCTION
OF $T/\bar{T}_s$ AND $X/\bar{T}_s$
T_o INITIAL SURFACE AIR TEMP. (°ABS.)
T FINAL SURFACE AIR TEMP. (°ABS.)
$\bar{T}_s$ AVERAGE SEA SURFACE TEMP. (°ABS.)
X HORIZONTAL DISTANCE (Km)
INITIAL SOUNDING:
TEMPERATURE DECREASES 0.5°C/100 m
$T/\bar{T}_s$
$X/\bar{T}_s$

PLATE II.

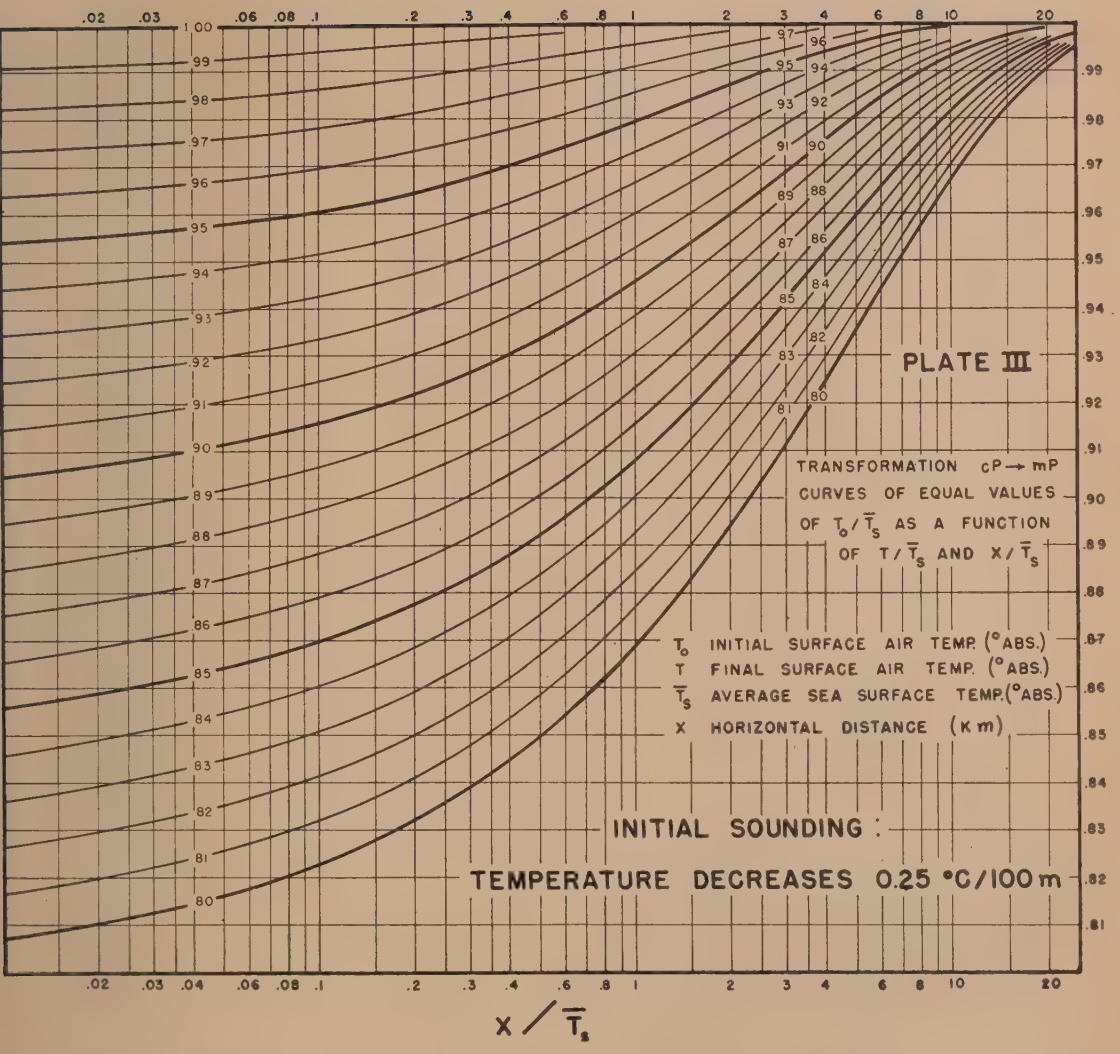
PLATE III
TRANSFORMATION cP → mP
CURVES OF EQUAL VALUES
OF $T_o/\bar{T}_s$ AS A FUNCTION
OF $T/\bar{T}_s$ AND $X/\bar{T}_s$
T_o INITIAL SURFACE AIR TEMP. (°ABS.)
T FINAL SURFACE AIR TEMP. (°ABS.)
$\bar{T}_s$ AVERAGE SEA SURFACE TEMP.(°ABS.)
X HORIZONTAL DISTANCE (Km)
INITIAL SOUNDING :
TEMPERATURE DECREASES 0.25 °C/100 m
$X/\bar{T}_s$

PLATE III.

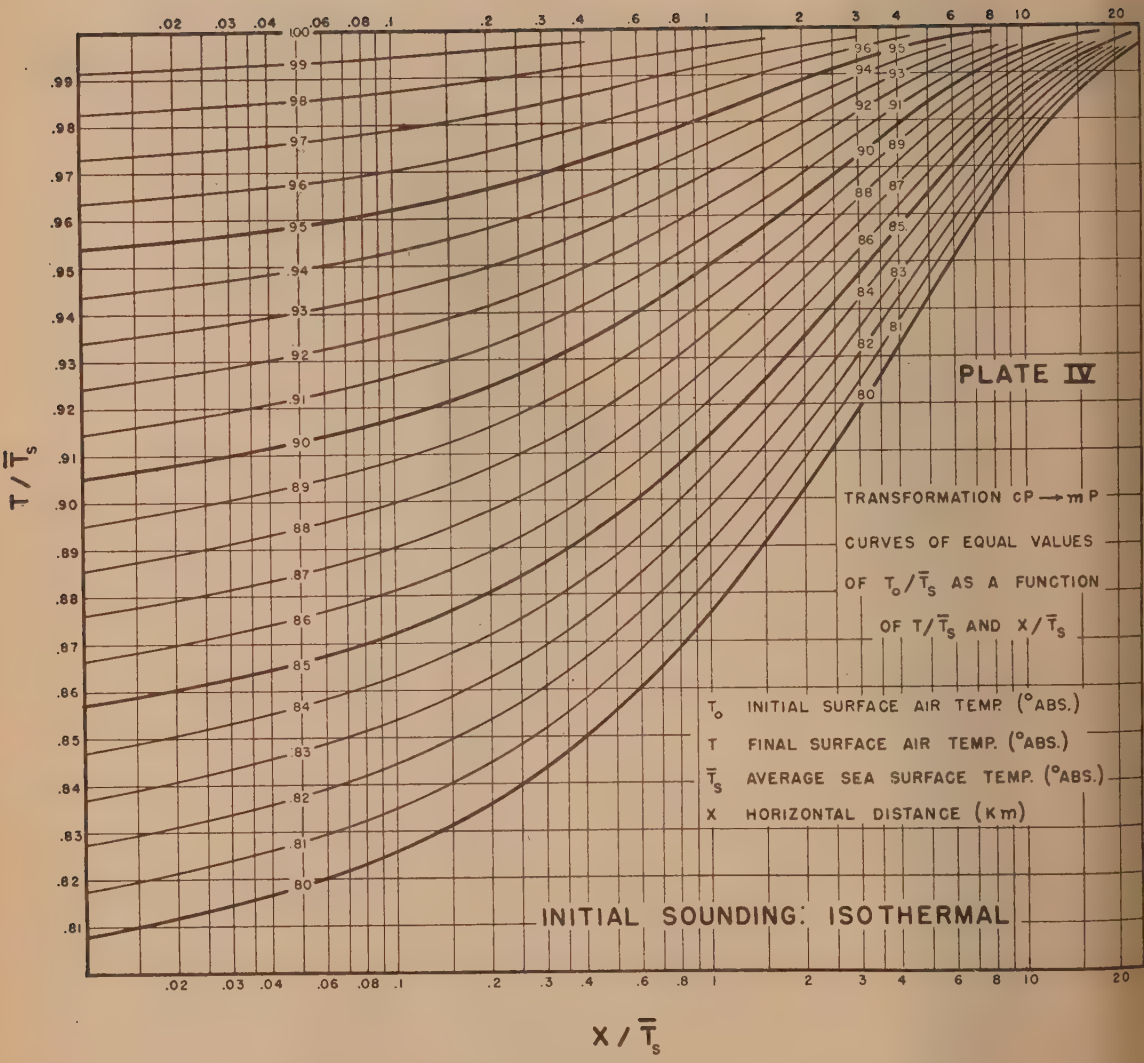
PLATE IV
TRANSFORMATION cP → mP
CURVES OF EQUAL VALUES
OF $T_o/\bar{T}_s$ AS A FUNCTION
OF $T/\bar{T}_s$ AND $X/\bar{T}_s$
T_o INITIAL SURFACE AIR TEMP. (°ABS.)
T FINAL SURFACE AIR TEMP. (°ABS.)
$\bar{T}_s$ AVERAGE SEA SURFACE TEMP. (°ABS.)
X HORIZONTAL DISTANCE (Km)
INITIAL SOUNDING: ISOTHERMAL
$T/\bar{T}_s$
$X/\bar{T}_s$

PLATE IV.

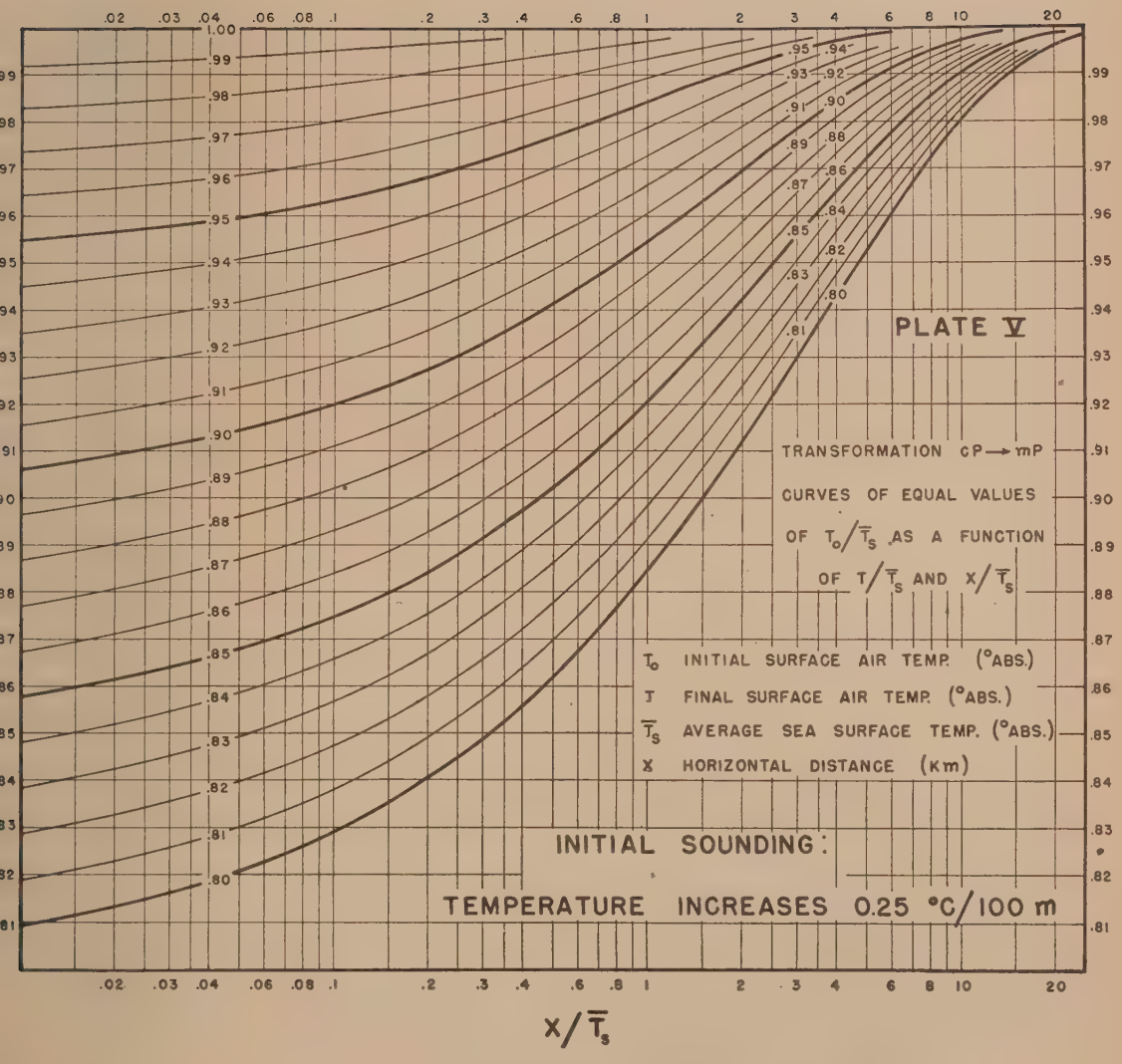
PLATE V
TRANSFORMATION cP → mP
CURVES OF EQUAL VALUES
OF $T_o/\overline{T}_s$ AS A FUNCTION
OF $T/\overline{T}_s$ AND $X/\overline{T}_s$
T_o INITIAL SURFACE AIR TEMP. (°ABS.)
T FINAL SURFACE AIR TEMP. (°ABS.)
$\overline{T}_s$ AVERAGE SEA SURFACE TEMP. (°ABS.)
X HORIZONTAL DISTANCE (Km)
INITIAL SOUNDING:
TEMPERATURE INCREASES 0.25 °C/100 m
$X/\overline{T}_s$

PLATE V

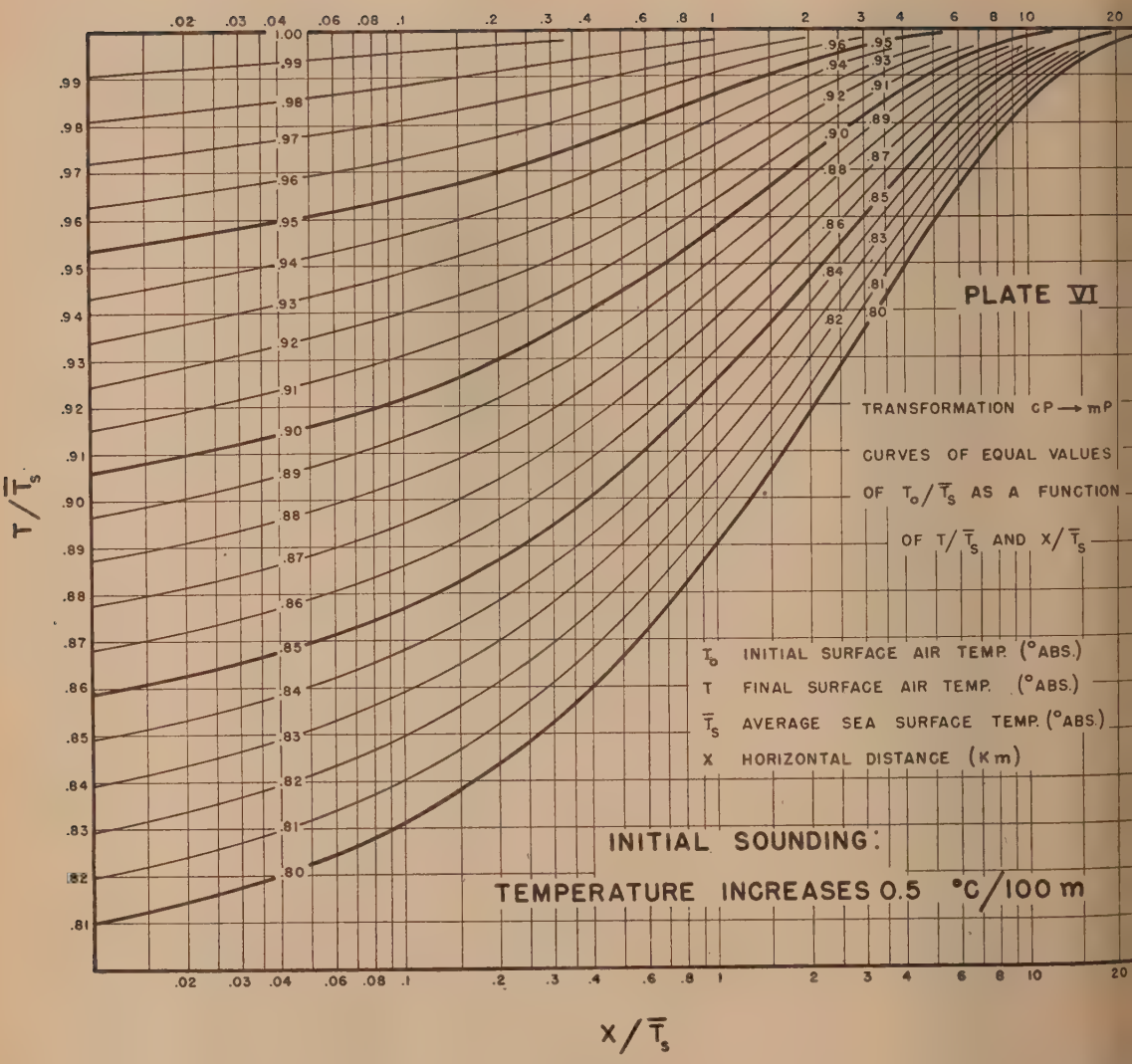
PLATE VI
TRANSFORMATION cP → mP
CURVES OF EQUAL VALUES
OF $T_o/\bar{T}_s$ AS A FUNCTION
OF $T/\bar{T}_s$ AND $X/\bar{T}_s$
T_o INITIAL SURFACE AIR TEMP. (°ABS.)
T FINAL SURFACE AIR TEMP. (°ABS.)
$\bar{T}_s$ AVERAGE SEA SURFACE TEMP. (°ABS.)
X HORIZONTAL DISTANCE (Km)
INITIAL SOUNDING:
TEMPERATURE INCREASES 0.5 °C/100 m
$T/\bar{T}_s$
$X/\bar{T}_s$

PLATE VI.

LIST OF CONTRIBUTIONS

from the

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New Series

For a list of Contributions Numbers 1 to 182 see previous issues from 1938 to 1942.

Number

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